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LOW-TEMPERATURE PUMPABILITY OF U.S. ARMY DIESEL ENGINE OILS

INTERIM REPORT
BFLRF No. 229

By

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Borderline oil-pumpability temperatures (BPT's) were determined for U.S. Army diesel engines by cranking experiments conducted in a cold box. The variables investigated included: four different diesel engine types; four different oil viscosity grades; and three different viscosity index improver chemical types. In general, for a given oil, the decreasing order of engine severity (i.e., highest BPT) was: the Continental LDT-465-1C and the Cummins VTA-903T were the most severe, and were approximately equivalent. The GM 6.2L engine was the next least severe with the DDC 6V-53T engine being the overall least severe. The different viscosity index improver chemistries of specially blended test oils included: olefin copolymer (OCP), styrene-isoprene polymer (SI), and polymethacrylate (PMA). The PMA-containing 15W-40 oils had superior low-temperature oil pumpability performance in each engine in which they were evaluated. The oils formulated with the SI VII had similar to slightly better low-temperature pumpability performance than the OCP-

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containing oils. The BPT's determined by ASTM D 3829 did not completely predict engine-derived BPT's. Predicted BPT's (D 3829) were either higher or lower than engine-derived BPT's depending on the individual engine involved. The linear regression correlation coefficients (R-squared) resulting from the two different BPT values ranged from 0.61 to 0.88. Based on the engine-derived BPT's, recommendations for revised low-temperature use limits for MIL-L-2104D oils were made.

FOREWORD

This work was conducted at the Belvoir Fuels and Lubricants Research Facility (SwRI), San Antonio, TX under Contract Nos. DAAK70-82-C-0001, DAAK70-85-C-0007 and DAAK70-87-C-0043 during the period July 1982 through December 1987. The work was funded by the U.S. Army Belvoir Research, Development and Engineering Center, Ft. Belvoir, VA, with Mr. F.W. Schaekel (STRBE-VF), as the Contracting Officer's Representative and Mr. T.C. Bowen (STRBE-VF) as the project technical monitor.

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I. INTRODUCTION AND BACKGROUND

A. Introduction

Under cold ambient conditions, lubricants will increase in viscosity to the point that they will not flow into the oil pump, or flow through the oil galleries. This form of oil starvation is especially critical to engines that require prompt and copious lubrication to the turbocharger. Heavy-duty diesel engines used primarily in commercial transport fleets generally do not experience low-temperature lubricant pumpability problems. These decreased problems are because of (1) less frequent cold starts, as equipment is often idled instead of shut down during cold-ambient periods and (2) use of supplementary electric engine block heaters in cold-weather locations. Diesel engine low-temperature pumpability is of concern to the U.S. Army because the combat-tactical fleet, which is powered primarily by diesel engines, must be ready to operate immediately at a wide variety of ambient temperatures throughout the world.

In a continuing effort to improve low-temperature operability, multiviscosity MIL-L-2104D diesel engine oils (15W-40) were introduced into the military supply system in early 1984.(1)* A need existed to better define the low-temperature use limits for multiviscosity and single-grade oils and apply these limits in the various lubrication orders for equipment.

B. Background

The vast majority of all previous work involving low-temperature oil pumpability was conducted in spark-ignition engines. In 1948, Appledoorn identified engine oil pumpability problems in winter with oils having high wax content and/or high viscosity at 0°F (-18°C).(2) Meyer conducted cranking determinations of military gasoline and diesel engines at arctic temperatures using oil that conformed to MIL-O-10295.(3) Moyer investigated oil pumpability of single and multigrade oils using an engine oil pump mounted in a pan.(4) Selby determined the viscosity/shear characteristics of reblends of the test oils from Moyer's work.(5) In 1967, the cold-cranking simulator was adopted to define low-temperature viscosity limits, and the extrapolated viscosity at 0°F (-18°C) was incorporated into the Society of Automotive Engineer's SAE Crankcase Oil Viscosity

*Underscored numbers in parentheses refer to the list of references at the end of this report.

Classification System (SAE J300a).(6-8) The cold-cranking simulator is intended to correlate with engine cranking, which is a high shear rate process; however, oil flow, which is a low shear rate process, was not addressed by a bench test at this time.

In the early 1970's, interest in oil pumpability accelerated due to increased gasoline engine warranty claims that were believed to be related to low-temperature oil properties. The SAE requested that American Society for Testing and Materials (ASTM) develop an oil pumpability bench test. This task was investigated by ASTM D2 RDD VII-C, Engine Oil Pumpability Task Force. The technical literature of the 1970's abounds with papers concerning the investigation and definition of low-temperature oil pumpability.(9-18) Studies were conducted in gasoline engines, viscometers, and bench-scale pumpability equipment.

In 1975, ASTM published the results of an extensive gasoline-engine based oil pumpability study.(19) Two oil pumpability failure modes were observed. Air binding occurred when the oil had sufficient gelation structure to prevent adequate oil flow to the oil pump. Air entering the oil pump caused both intermittent and continuous oil-pressure loss. Air binding was characteristic of relatively short, large diameter oil pickup tubes. The other pumpability failure mode was the flow-limited condition in which the oil was too viscous for an adequate flow rate. Oil pickup tubes with a relatively long length and small diameter were most sensitive to flow-limited failures.(19,20)

At this point, research was directed towards developing a laboratory bench test that would respond to both air-binding and flow-limited oils. Several techniques were evaluated by the ASTM Test Method Task Force. A low shear rate apparatus, the mini-rotary viscometer (MRV), was selected as the test method that best related to the engine performance data (21) and was approved as ASTM Method D 3829.(22) The MRV requirements for winter-grade engine oils were incorporated into SAE Viscosity Classification System J-300 SEP80.(23) ASTM D 3829 (MRV) defines maximum values for yield stress (< 105 Pa) and apparent viscosity (30 Pa·S). The yield stress is related to the air-binding tendency of the oil and is defined as the minimum stress required for oil flow, which is a measure of the gelation strength of the oil. The apparent viscosity limit is related to the flow-limited type of pumpability failure.

Despite the newly adopted low-temperature viscosity specification J-300 SEP80, severe engine oil pumpability failures occurred in spark-ignition engines during the winters of

1980 through 1983.(24-31) The oil pumpability related engine failures precipitated a new round of research to determine why the MRV test method was inadequate.(24-31) The sensitivity of some oils to cool-down rate was found to be the reason for the failure of the MRV test to identify oils with poor low-temperature performance.(24-26,31)

In 1987, MacAlpine and May reported that basestock pour points or residual wax contents alone do not predict low-shear viscometric properties of formulated engine oils under slow-cool conditions. The wax composition was reported to be a key factor with both normal and non-normal paraffins contributing to low-temperature viscosity increases.(32) The Stable Pour Point Test, Cycle C (FTM 791b, Method 203) was found to identify many, but not all, of the low-temperature problem oils.(31) The Stable Pour Point was included in the SAE Viscosity Classification System with requirements for 10W and 5W graded oils (SAE J300APR84).(31) Additional work is continuing on revising and defining cooling cycles for the MRV apparatus.

II. OBJECTIVE/APPROACH

The objective of this program was to define the minimum temperatures at which multiviscosity and straight-grade lubricants procured under military engine oil specifications may be used in U.S. Army diesel engines and still provide adequate low-temperature lubrication. The approach was to determine the low-temperature oil pumpability characteristics of several U.S. Army engines using a variety of engine oils. This determination was accomplished by placing the subject engine in a cold box, charging it with test oil, and then cooling at prescribed conditions to the test temperature. The engine was then cranked at idle speed (without firing), and the time to a constant oil pressure was determined. An underlying assumption was that in the field, an Army engine will be started and idled by a slave engine and/or starting aids. The program was designed to ensure that the idling engine will be properly lubricated at low temperatures.

III. EQUIPMENT/PROCEDURE

A. Test Engines

Representative two- and four-cycle diesel engines were selected from the U.S. Army fleet for this work. The diesel engines investigated were:

- Teledyne-Continental Motors LDT-465-1C
- GM 6.2L
- Cummins VTA-903-T
- DDC 6V-53T

Of the various LD-465 configurations available, the engine with the longest pickup tube was selected. Additional descriptions of each engine are presented in later sections.

B. Test Cell Description

A refrigerated box was used to cool the test engines to the desired test temperatures. The box was able to attain test temperatures as low as -40°F (-40°C) and maintain them ±2°F. The refrigeration equipment was controlled using a Honeywell UDC-500 controller and a Honeywell DPC-7700 set point programmer. This equipment allowed specification of cooling rates as described later.

Initially a 50-horsepower motoring dynamometer was used to motor the test engines at the desired speeds. This system proved to be difficult to use since the torque available at low speeds (800 to 1000 rpm) was very limited. As a result of this problem, and a fuel-dribble problem, discussed later, the pistons and connecting rods were removed from the first test engine (the Continental LDT-465-1C). This action lowered the motoring friction and made the use of the motoring dynamometer possible. Eventually, this approach was questioned since the connecting-rod lubrication system was eliminated with this approach. The pistons and connecting rods were reinstalled and an engine-powered motoring system was used. This design consisted of a driving engine, a clutch, a 12-speed truck transmission, and a driveshaft through the cold-box wall connecting the transmission to the flywheel of the test engine (Fig. 1). The clutch on the transmission was actuated with an air cylinder such that air pressure was required to disengage the clutch. A needle valve was used to control the air bleed rate from the cylinder and thus control the engagement rate of the clutch. Cranking speeds of 150 to 1000 rpm were possible using this cranking apparatus. Speeds lower than 150 rpm caused excessive torsional vibrations in the driveshaft and were avoided.

The fuel system of the first engine tested (the Continental LDT-465-1C) was plumbed to circulate fuel through the injection system for lubrication. However, dribble from the

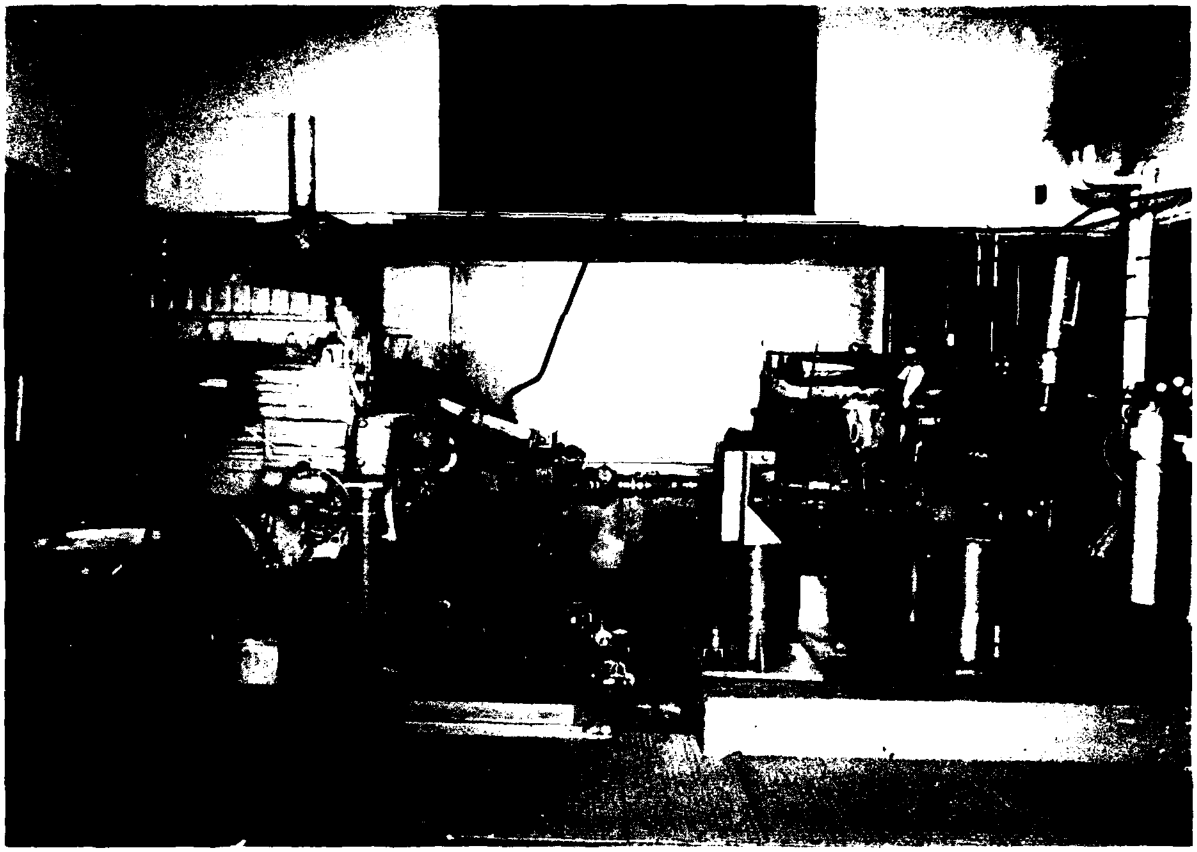


Figure 1. Cummins engine used to crank LDT-465-1C engine

injectors (even in the no-rack position) caused exhaust fumes to fill the refrigerated box. As a result, each of the fuel systems in the test engines was disabled in order to prevent exhaust fumes from being present in the box. Appendix A contains details of the measures taken to disable the fuel systems.

The normal engine-mounted water pump was used to circulate a 50/50 volumetric blend of antifreeze and water in the cooling passages of the engine. A 1000-watt immersion heater was plumbed in the cooling line to facilitate warmup of the engine for purposes of oil flush. Circulation ran from the engine to the water pump to the heater and back to the engine. Four 250-watt infrared heating lamps were placed under the oil sumps of the engines. These lamps provided rapid heat up of the oil sump without disturbing the internal oil-pan geometry with heating coils.

C. Instrumentation

A Honeywell UDC-500 controller was used to control the temperature in the cold box. The controller received its set point from a Honeywell DCP-7700 set point programmer, which allowed controlled cool-down curves with respect to time. Since initial tests with the cold box revealed a tendency to freeze the evaporator coils on humid days, a defrost cycle was added to eliminate the icing. The defrost was set to initiate at midnight and last for 30 minutes. This defrost cycle effectively eliminated the icing problem but only introduced a slight perturbation into the cool-down cycle. Since the oil sump had significant thermal mass, the perturbation in the cool-down cycle had minimal impact on the bulk oil temperature.

Each engine was instrumented for oil-sump temperature, oil-suction pressure (in the oil pickup tube), oil-gallery pressure, turbocharger oil pressure (where applicable), engine speed, and in some cases, rocker-arm oiling indication/pressure. The air temperature in the cold box was also measured.

Rocker arm oiling was measured in one of two ways. In the case of the Cummins VTA-903T and DDC 6V-53T engines, a 15-psig pressure transducer was plumbed directly to the rocker shaft. This configuration was possible since both engines use a pressurized rocker shaft. In the case of the GM 6.2L engine, however, a pressurized push rod lubricates the rocker arm by drip feed. In order to obtain an indication of rocker arm oiling, a vacuum system was used to indicate the presence of oil in the rocker arm. Fig. 2 shows the rocker arm oiling indication system for the 6.2L engine. A detailed description of the test set up and installation is given in Appendix A.

D. Test Lubricants

A wide variety of diesel engine lubricants was evaluated during this program. The oils included special oils blended to a given viscosity, qualified products from MIL-L-2104D qualified products list, and commercially available oils. A variety of viscosity index improver (VII) additives were represented in the test oil matrix. Oils that exhibit cooling-cycle sensitivity (problem oils) were not included in the matrix. Since MIL-L-2104D oil specification includes a stable pour point requirement, it was felt that most problem oils would be eliminated from the military supply system. Also, future low-

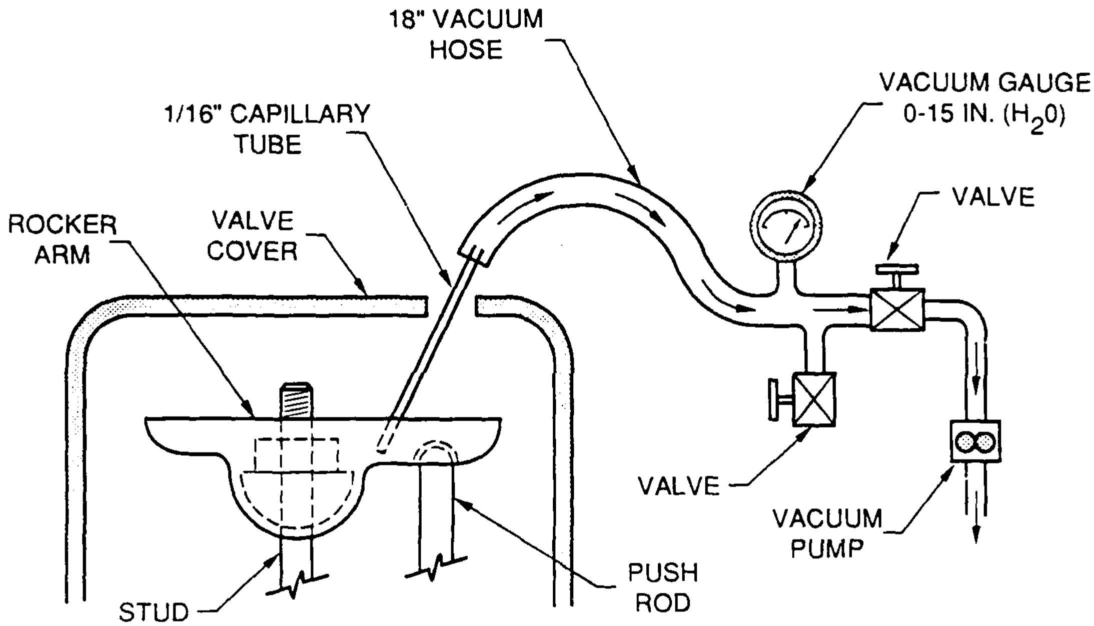


Figure 2. Rocker arm oiling indicating system, GM 6.2L engine

temperature specifications will include cooling cycles and procedures to identify and eliminate "problem oils." Each drum of test lubricant was stored in an electrically heated water bath for at least 24 hours prior to testing and for the duration of testing. The temperature of the lubricant was maintained at 180°F (82°C) in order to provide all test lubricants with uniform temperature histories and destroy any previous temperature history.

The properties of the 15W-40 oils used in this program are presented in TABLE 1. Oil No. 1 is a MIL-L-2104D qualified product that was recently used in a field validation test (FVT) of 15W-40 oils at Ft. Bliss, TX.(33) Oil No. 2 is the MIL-L-2104D, 15W-40 grade Army reference oil and was used in the recent 15W-40 FVT at Ft. Knox, KY.(33) Oil Nos. 1 and 2 contain different olefin-copolymer VII systems. Oil Nos. 3 through 8 are special blends supplied by Rohm and Haas Company. Included are two of each oil based on olefin copolymer (OCP), polymethacrylate (PMA) and styrene-isoprene (SI) VI improvers, with each polymer-type oil formulated to the upper limit of SAE 15W in one case, and to the lower limit of SAE 15W in the second case. The oils supplied by Rohm and Haas are "well-behaved", that is, they have no major soak-time sensitivity. Compositions of the PMA and OCP special-blend oils are presented in TABLE 2. The oils were formulated with a detergent-inhibitor package to API SF/CD performance levels.

TABLE 1. Lubricant Properties
(15W-40 Test Oils)

Lubricant No. / Description	ASTM Method	1 Qualified MIL-L-2104D	2 Qualified MIL-L-2104D	3 OCP-L	4 OCP-H	5 SI-H	6 SI-L	7 PMA-L	8 PMA-H	9 Comm. PMA	10 Comm. SI
Properties											
K. Vis., 40°C, cSt	D 445	107.47	99.06	101.51	111.86	107.01	98.39	88.48	97.87	95.42	98.98
K. Vis., 100°C, cSt	D 445	13.66	13.31	14.90	14.65	13.97	14.51	15.02	14.58	14.20	14.34
Viscosity Index	D 2270	126	133	153	134	131	152	179	155	153	134
API Gravity, °	D 287	28.6	29.8	29.8	28.9	29.3	30.2	28.9	28.3	27.4	28.8
Pour Point, °C	D 97	-24	-26	-27	-27	-23	-25	-28	-28	-33	-24
Borderline Pumpability, Temp °C	D 3829	-25.2	-27.3	-27.7	-26.3	-25.8	-28.6	-30.1	-28.2	-29	-27.6
Apparent Viscosity,	D 2602										
cp at -15°C		2900	2830	1950	3400	3250	2000	1950	3300	3200	2750
cp at -20°C		7000	ND*	4100	6750	6800	3900	4200	7150	5800	5600
cp at -25°C		ND	ND	8500	13900	ND	ND	9000	15600	ND	ND
Total Acid No.	D 664	3.0	2.6	2.9	2.8	2.8	2.6	2.9	3.0	3.3	2.6
Total Base No.	D 664	7.0	5.4	5.6	5.6	5.6	5.1	5.3	5.5	6.2	8.0
Sulfated Ash, wt%	D 874	0.91	1.09	0.92	0.92	0.90	0.92	0.90	0.89	1.04	0.97
Element, wt%	Method										
Ba	ICP	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.005	<0.005	<0.005	<0.005
Ca	ICP	<0.005	0.15	0.20	0.21	0.18	0.19	0.20	0.20	0.21	0.21
Mg	ICP	0.15	<0.05	<0.005	<0.005	<0.005	<0.005	0.005	<0.005	<0.005	<0.005
Zn	ICP	0.13	0.16	0.15	0.15	0.16	0.16	0.15	0.15	0.16	0.13
P	ICP	0.11	0.14	0.13	0.13	0.11	0.12	0.13	0.13	0.13	0.12
S	XRF	0.51	0.55	0.48	0.47	0.41	0.43	0.44	0.47	0.94	0.40
N	CLM	0.07	0.05	0.09	0.09	0.09	0.10	0.06	0.06	0.11	0.12

* ND = Not Determined.

TABLE 2. Compositions of Special Oil Blends SF/CD Performance Level

Oil Composition, wt%	Oil No. 3 Low 15W (OCP-L)	Oil No. 4 High 15W (OCP-H)	Oil No. 7 Low 15W (PMA-L)	Oil No. 8 High 15W (PMA-H)
Dispersant PMA VII	0	0	7.5	5.7
Nondispersant OCP VII	12.2	9.0	0	0
Ashless Dispersant	2.5	2.5	0	0
Detergent-Inhibitor Package	9.1	9.1	9.1	9.1
Basestock 10	35.8	0	25.6	0
Basestock 20	40.4	70.0	57.8	63.0
Basestock 35	0	9.4	0	22.2

Because the OCP VII was a nondispersant type, ashless dispersant was included in the formulation of oil Nos. 3 and 4. Oil No. 9 is a commercially available 15W-40 product that is branded and sold by a major diesel engine manufacturer. Oil No. 10 is a well-regarded commercial oil (CD) from a major petroleum company.

The properties of the other (non-15W-40) oils investigated during this program are presented in TABLE 3. Oil No. 11 is a qualified MIL-L-2104D grade 30 product of 76 VI that is near the specification minimum limit. Considering low-temperature viscosity properties, oil No. 11 is actually a 25W-30 grade. Oil No. 12 is the MIL-L-2104D grade 30 (actually 20W-30) reference oil, and oil No. 13 is the grade 10W MIL-L-2104D reference oil.

Oil No. 14 is a 10W-30 special blend oil supplied by Rohm and Haas that contains an OCP VII and is similar in composition to 15W-40 oils No. 3 and 4. This 10W-30 is blended to the lower limit of SAE 10W. Oil Nos. 15 through 17 are commercially available products that contain synthetic basestock material. Oil No. 16 is a qualified MIL-L-46152 grade 5W-30 oil that contains polyalphaolefin basestocks. Oil No. 17 is a recent revision of oil No. 15 and has been qualified under MIL-L-2104D as a 15W-40 product. The basestocks of oil Nos. 15 and 16 are blends of polyol ester and polyalphaolefin materials.

TABLE 3. Low-Temperature Pumpability Test Oils

Lubricant No.		11	12	13	14	15	16	17
Viscosity Grade		SAE 30 (25W-30)	SAE 30 (20W-30)	10W	10W-30	5W-30	5W-30	5W-40
Description		MIL-L-2104D Qualified Products			OCP-L	Synthetic Oils		
Properties	ASTM Method							
K. Vis., 40°C, cSt	D 445	124.17	95.82	39.95	64.19	56.0	61.97	85.95
K. Vis., 100°C, cSt	D 445	11.62	11.08	6.25	10.59	10.0	10.26	15.21
Viscosity Index	D 2270	76	101	103	155	167	154	188
API Gravity, °	D 287	23.9	26.8	29.0	30.7	31.0	35.2	31.3
Pour Point, °C	D 97	-21	-24	-33	-27	-46	<-51	-39
Borderline Pumpability Temp, °C	D 3829	-17.3	-22.4	-33.8	-28.3	-32.0	<-40	<-40
Apparent Viscosity, cp at -15°C	D 2602 5250	1425 at -5°C	ND* at -5°C	870	1170	ND	ND	
cp at -20°C		ND	ND	3050	2150	1650	3900 at -30°C	ND
cp at -25°C		9600 at -10°C	3150 at -10°C	6400	6000	2550	2250	2300
Total Acid No.	D 664	2.4	2.6	2.5	2.4	3.0	3.3	3.5
Total Base No.	D 664	10.9	7.4	7.3	5.5	6.3	8.0	13.9
Sulfated Ash, wt%	D 874	1.51	0.91	0.90	0.89	1.10	1.00	1.45
Elements, wt%	Method							
Ba	ICP	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Ca	ICP	0.27	<0.005	<0.005	0.21	0.25	<0.005	0.16
Mg	ICP	0.08	0.155	0.15	<0.005	<0.005	0.17	0.15
Zn	ICP	0.13	0.13	0.13	0.15	0.13	0.11	0.12
P	ICP	0.12	0.12	0.11	0.12	0.13	0.12	0.10
S	XRF	0.61	0.54	0.46	0.44	0.33	0.56	0.20
N	CLM	0.04	0.00	0.06	0.09	0.14	0.05	0.07

*Note: ND = Not determined
ICP = Inductively coupled plasma
XRF = X-ray fluorescence
CLM = Chemiluminescence method

E. Test Procedure

The test procedure used for the lubricant pumpability determinations is described in Appendix B.

The timetable shown in the procedure was intended to provide each run with the same amount of cold-soak time, while still allowing adequate time to change lubricant and prepare for the next day's run. In some instances, the cold soak was extended over a weekend to investigate the effect of longer cold-soak periods. Normal cold-soak time was 20 hours total, with over-the-weekend tests consisting of 68-hour cold-soak periods.

Initially, in the LDT-465-1C engine, a fast-cooling cycle (82CP) was used. The oil was cooled quickly (approximately 2 hours) to the test temperature and held at test temperature approximately 18 hours until the pumpability test was started. This procedure was changed as information on the critical nature of oil cooling rate on pumpability of some engine oils became available in the literature. The new slower oil cooling procedure (84CP) used was essentially the "Sioux Falls" cycle (SFC) that included a programmed stepwise cooldown.(25) In the 84CP cooling procedure, the oil was cooled as fast as possible to a point 14°F above the desired pumpability test temperature and held there for 8 hours. During the next 8 hours, the temperature was slowly reduced 14°F to the desired test temperature and then held there 1.5 hours prior to attempting to pump the oil. During the 8-hour slow cooldown, the temperature is reduced 1°F over 2 hours, 2°F over the next 2 hours, 4°F over the next 2 hours, and 7°F over the last 2 hours. A schematic of the staged programmed cooling cycle is presented in Fig. 3.

F. Typical Oil Pressure Traces

When engine oil is pumped at low temperature in an engine, the amount of engine oil flowing is indicated by the oil pressure. Typical oil pressure traces are presented in Fig. 4.(19) A satisfactory condition is defined as adequate oil pressure within some minimum amount of time. Unsatisfactory oil pumping performance can be classified in the following four categories:

- flow limited
- typical borderline

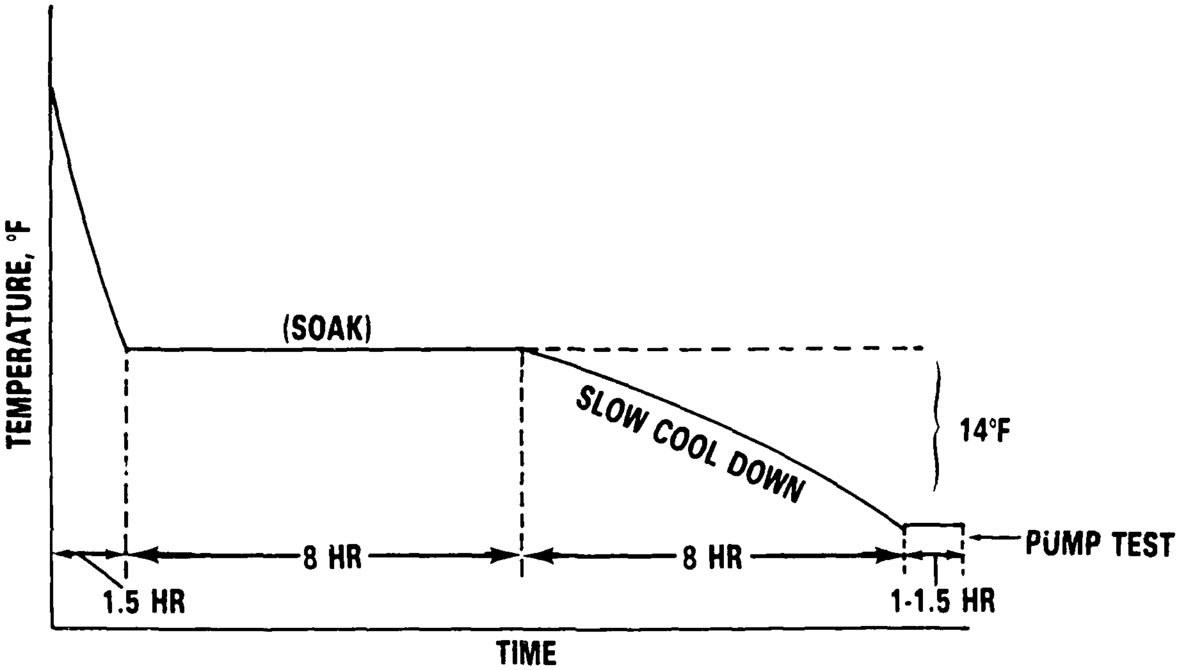


Figure 3. Cooldown cycle (84CP) schematic

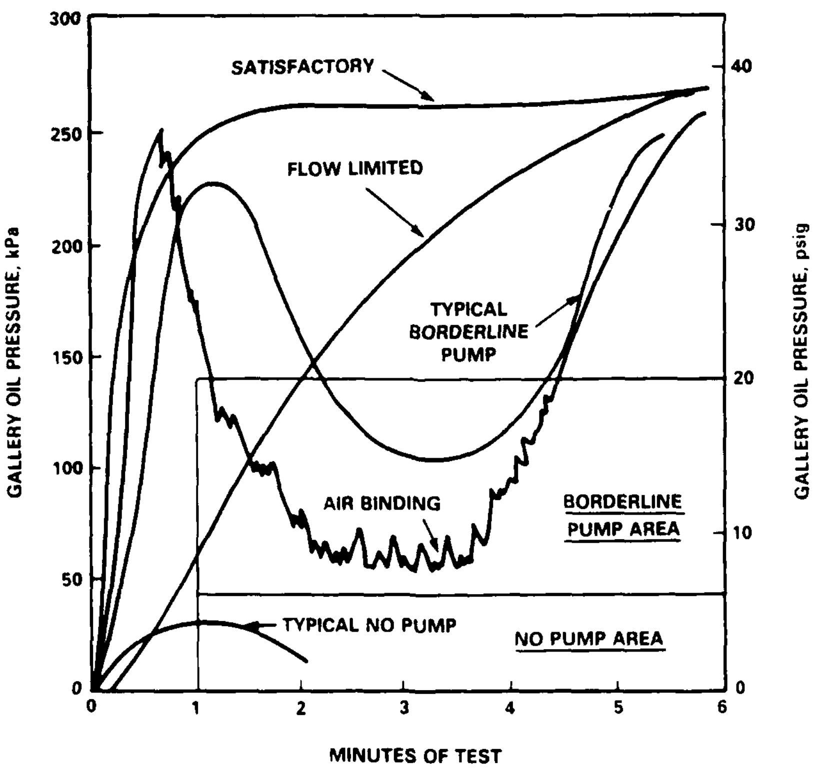


Figure 4. Typical oil pressure traces

- air binding
- no pump

In the flow-limited condition, adequate oil pressure develops; however, it does not occur within the minimum time due to inadequate oil flow. Typical borderline pump condition is characterized by initial adequate oil pressure, followed by inadequate pressure as the pump cannot move enough of the viscous oil and then recover to acceptable pressure as the system warms and oil viscosity reduces. A specialized type of borderline pumping is the air-binding condition, where the oil gel structure does not allow sufficient oil to flow to the oil pump pickup. As the oil is pumped away without total resupply, the oil pump intermittently sucks air that appears as sharp spikes on the oil pressure trace. The "no pump" condition occurs when the oil is too thick to be pumped at all. All of these conditions were observed within the matrix of oils and Army engines investigated during this program.

IV. RESULTS

A. LDT-465-1C Engine

The first engine to be investigated for low-temperature oil pumpability was the Continental LDT-465-1C used to power many of the U.S. Army tactical 2.5- and 5-ton trucks. The initial tests were run without engine pistons installed to reduce the breakaway torque requirements. Later tests were run with the pistons installed when a better cranking system was installed. A description of the LDT-465-1C engine is presented in TABLE 4. A photograph of the test engine installed in the cold box is Fig. 5. A schematic of the LDT-465-1C engine lubrication system is presented in Fig. 6, along with locations of the pressure pickup instrumentation. Turbocharger oil pressure was obtained from the oil feed line to the turbocharger; engine oil pressure was obtained from the main oil gallery at the rear of the engine; and oil pump inlet pressure was obtained from the midpoint of the oil pickup tube that runs between the front and rear sections of the oil pan.

Borderline pumping conditions for this engine at 600 rpm idle were defined as a minimum oil pressure of 40 psi at 1.0 minute and thereafter. The oil pressure limit was

TABLE 4. Engine Specifications for the Continental LDT-465-1C Engine

Model:	LDT-465-1C
Engine Type:	Four-Cycle, Compression Ignition, M.A.N. Combustion System, Turbocharged
Cylinders:	6 Inline
Displacement:	7.83 L (478 cubic inches)
Bore:	11.58 cm (4.65 inches)
Stroke:	12.37 cm (4.87 inches)
Compression Ratio:	22:1
Fuel Injection:	Bosch Rotary Distributor w/Density Compensation
Rated Power:	145-156 kW (194-209 BHP) at 2800 rpm
Rated Torque:	597 NM (429 lb-ft) at 2000 rpm
Idle Speed:	600 rpm (motoring speed for pumpability tests)

selected based on the minimum oil pressure at idle listed in the Army training manual for the LDT-465-1C engine.(34) Gallery and turbocharger oil pressure were developed at the same time in this engine; thus, all borderline pumping determinations were made based on the gallery oil pressure. In general, the engine exhibited flow-limited behavior at temperatures well below the borderline pumping temperature (BPT) and air binding at temperatures near the BPT. Fig. 7 shows a typical oil pressure trace at borderline conditions in the LDT-465-1C engine.

A comparison was made between the BPTs obtained with and without pistons installed in the LDT-465-1C engine. As shown in TABLE 5, the BPTs were essentially equivalent with or without the pistons present.

The effect of the cooling cycle on the BPT of four different test oils was determined. As shown in TABLE 6, no major differences in BPT were observed for these four oils when tested using the fast- or slow-programmed cooling cycles. The two multigrade oils had slightly higher BPTs when using the slow-cool method. Thus, the slow-cool method was equivalent or possibly just slightly more severe than the fast-cool method. The programmed slow-cool cycle was used for all subsequent tests in different engines.

The effect of an extended cold soak on oil BPT in the LDT-465-1C engine was determined. The extended weekend soak consisted of following the normal slow-cooling cycle up to the point at which the cranking test would normally be made. At this point,

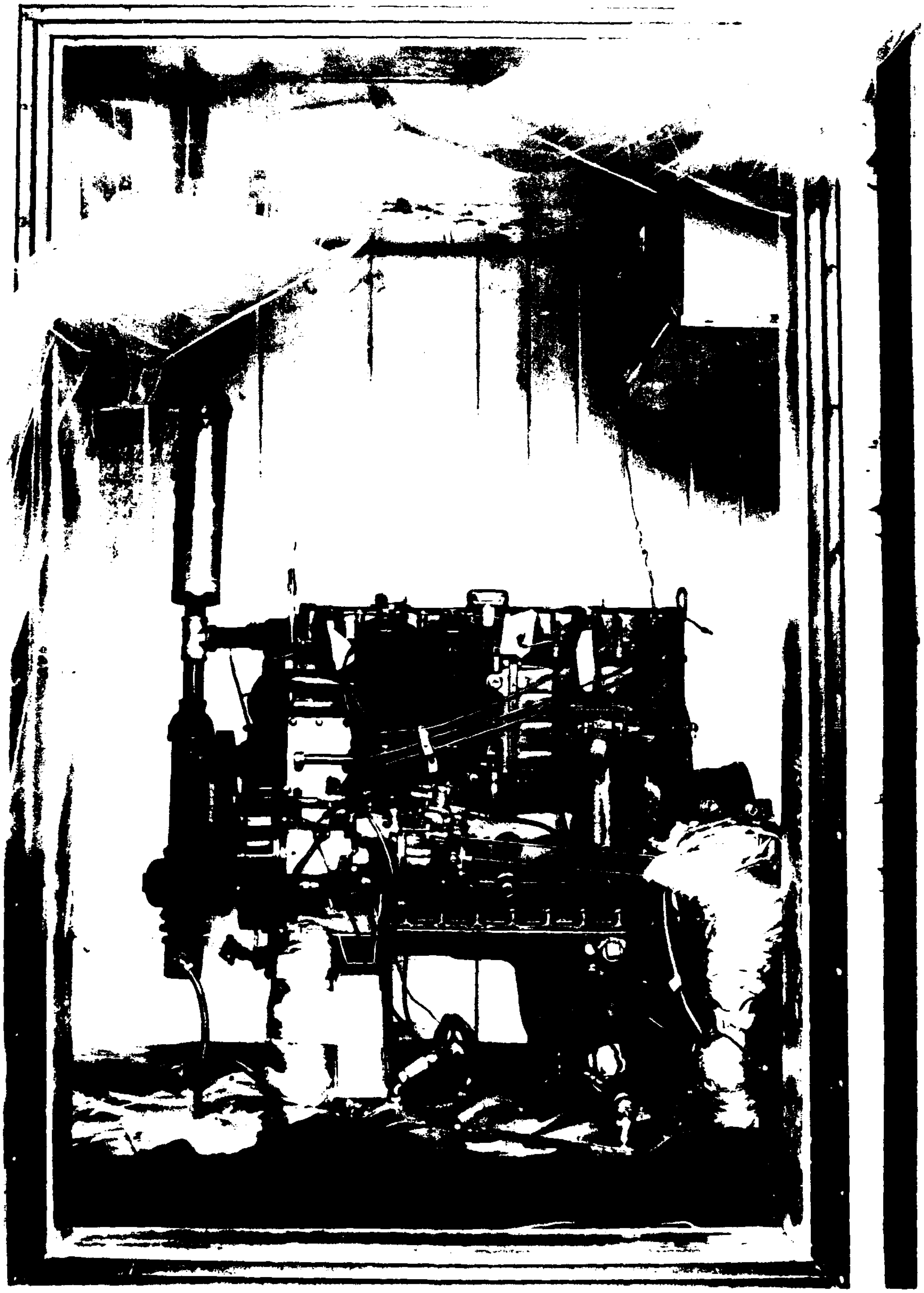


Figure 5. LDT-465-1C engine in cold box

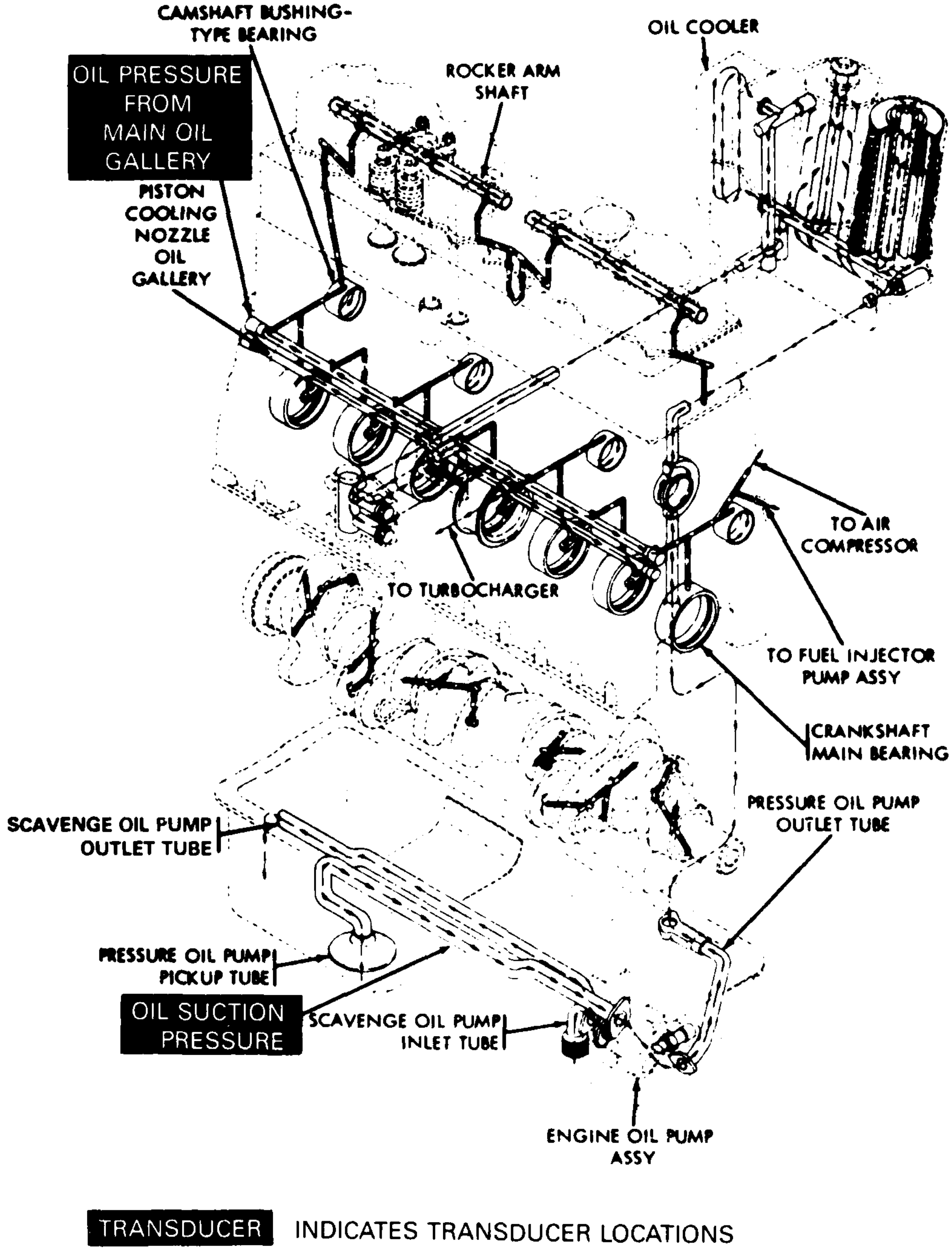


Figure 6. Lubrication system diagram for LDT-465-1C engine

48 hours were added to the cold soak before testing began, which increased the total extended soak test time to 68 hours. As shown in TABLE 7, the extended cold soak had no major effect on oil BPT.

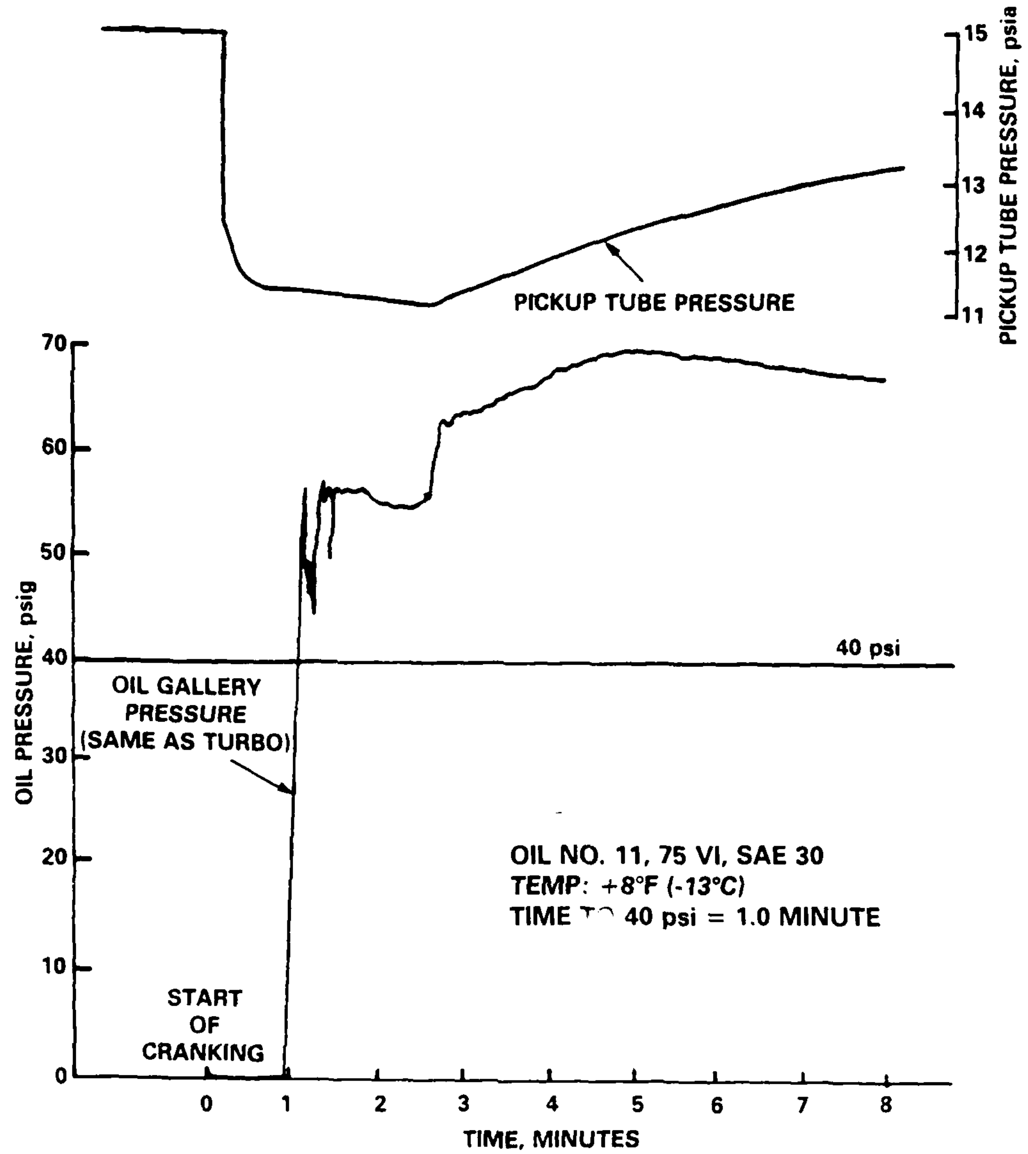


Figure 7. Typical LDT-465-1C oil pressure trace

TABLE 5. Effect of Pistons on Borderline Pumpability Temperature, LDT-465-1C Engine, Fast-Cool Procedure

	15W-40 Oils			
	PMA VII		OCP VII	
	Oil No. 7	Oil No. 8	Oil No. 3	Oil No. 4
With Pistons Installed	-20°F(-29°C)	-17°F(-27°C)	-10°F(-23°C)	-6°F(-21°C)
Without Pistons	-18°F(-28°C)	-16°F(-27°C)	-10°F(-23°C)	-5°F(-21°C)

TABLE 6. Cooling Cycle Effect—LDT-465-1C Engine

Oil No.	Description	Fast Cool 82CP	Programmed Slow Cool 84CP
1	15W-40	-8°F(-22°C)	-4°F(-20°C)
12	SAE 30	-4°F(-20°C)	-4°F(-20°C)
13	10W	-22°F(-30°C)	-22°F(-30°C)
4	15W-40 OCP-H	-6°F(-21°C)	-4°F(-20°C)

TABLE 7. Extended Soak Time Effect LDT-465-1C Engine, 82CP

Oil No.	Description	Time to 40 psi Oil Gallery Pressure, min	
		Normal Soak (20 Hr)	Extended Soak (68 Hr)
13	10W at -24°F(-31°C)	1.63	1.70
7	15W-40, PMA-L at -18°F(-28°C)	0.65	0.75

The results of low-temperature oil pumpability evaluations in the LDT-465-1C engine are presented in TABLE 8. Since the two cooling procedures (slow and fast programmed) yielded essentially the same BPTs, all data are presented. Some of the oils were received later in the program and were not evaluated in this engine and are reported as not tested. Appendix C contains plots of test temperature versus time to minimum required oil pressure for the LDT-465-1C engine. For the multigrade oils, the only points plotted were for tests of new unsheared oils. To conserve oil, multigrade oils were re-run to help in locating the approximate BPT. However, the actual BPT was always confirmed using new, unsheared multigrade oil. For the 15W-40 oils, Oil No. 1, which contains an OCP VII system, and special blend Oil No. 4 (OCP-H) were the most severe oils with each having a BPT of -4°F (-20°C). For blends of equivalent low-temperature viscosities, those containing PMA VII additive had substantially lower BPTs than the oils formulated with OCP VII. Oil No. 11 (75 VI) had the most severe SAE 30 grade BPT at +6°F(-14°C), while the straight 10W grade (Oil No. 13) had a BPT of -22°F (-30°C). Overall, the BPTs developed in the LDT-465-1C were more severe (higher

TABLE 8. Oil Borderline Pumpability Temperature (BPT) in LDT-465-1C Engine

Oil No.	Oil Description	Cooling Cycle	BPT, °F(°C)	MRV/BPT, °F(°C)
	15W-40 Oils			
1	MIL-L-2104D (OCP)	84CP	-4(-20)	-13(-25)
2	MIL-L-2104D (OCP)	82CP	-8(-22)	-16(-27)
3	OCP-L	82CP	-10(-23)	-18(-28)
4	OCP-H	84CP	-4(-20)	-16(-27)
5	SI-H	NT	NT	-15(-26)
6	SI-L	NT	NT	-18(-28)
7	PMA-L	82CP	-20(-29)	-22(-30)
8	PMA-H	82CP	-17(-27)	-19(-28)
9	Commercial PMA	NT	NT	-20(-29)
10	Commercial SI	NT	NT	-17(-27)
	30-Grade Oils			
11	MIL-L-2104D 75 VI	84CP	+6(-14)	+1(-17)
12	MIL-L-2104D	84CP	-4(-20)	-8(-22)
	Others			
13	10W MIL-L-2104D	84CP	-22(-30)	-29(-34)
14	10W-30, OCP-L	82CP	-12(-24)	-19(-28)
15	5W-30, Synthetic	NT	NT	-26(-32)
16	5W-30, Synthetic	84CP	<-33(-36)	< -40(-40)

NT = Not tested.
OCP = Olefin copolymer VII.
SI = Styrene-Isoprene VII.
PMA = Polymethacrylate VII.

temperature) than the BPTs calculated from the MRV (ASTM D 3829). A plot of the linear regression of engine-derived BPT on MRV BPT is presented in Fig. 8, and a summary of the regression analysis is in TABLE 9. In Fig. 8, the two pairs of dotted lines represent the 95-percent confidence and prediction limits. Based on this linear regression, which has a correlation coefficient (R-squared) of 0.86, approximately 86 percent of the variability in the engine-derived BPT is explained by the MRV BPT. In general, the engine-derived BPT was approximately 6°F higher than the MRV BPT.

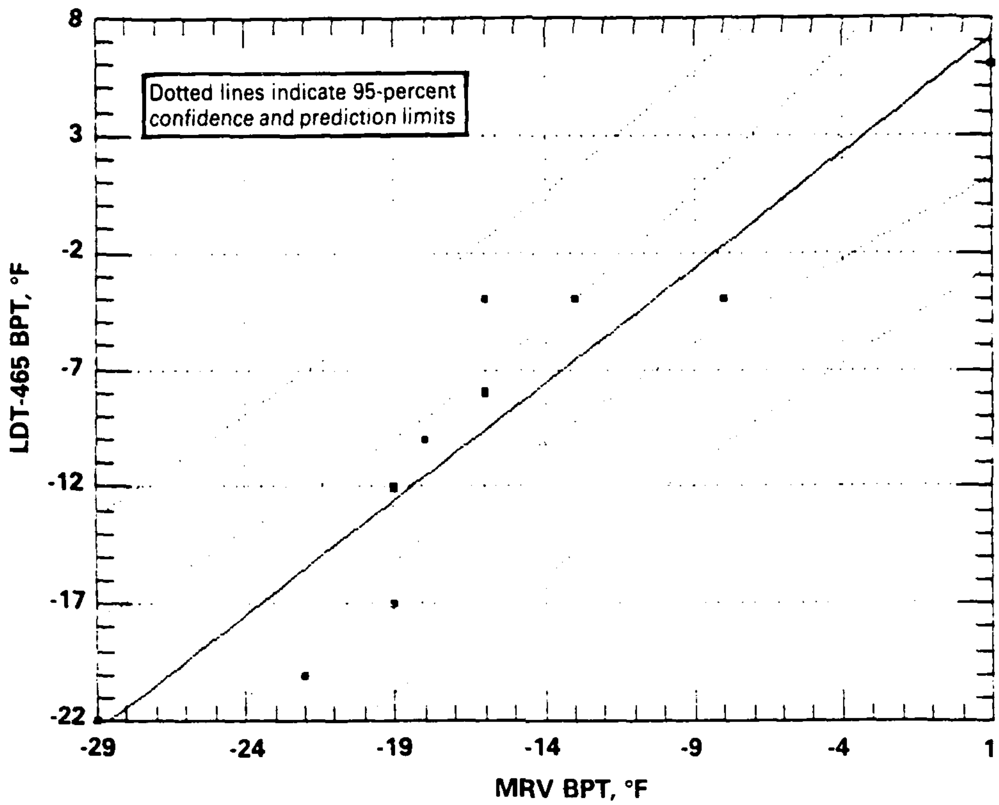


Figure 8. Regression of LDT-465 BPT on MRV BPT

TABLE 9. BPT Regression Analysis—LDT-465-1C Engine

Regression Analysis - Linear model: Y = a+bX
Dependent variable: LDT465BPT   Independent variable: MRVBPT

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.1732	2.44399	2.52587	0.0354826
Slope	0.985736	0.13843	7.12082	9.99193E-5

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	572.21982	1	572.21982	50.70613	0.00010
Error	90.280183	8	11.285023		
Total (Corr.)	662.50000	9			

Correlation Coefficient = 0.92937   R-squared = 0.86
Std. Error of Est. = 3.35932

The 15W-40 multigrade oils experienced shear during the pumping test. TABLE 10 shows the effect of a single pump test on oil properties. The oils lost between 0.2- to 2.2-centistokes viscosity at 100°C, and most oils had slightly lower MRV BPTs after experiencing one pump test. Cold-cranking simulator viscosities were slightly reduced in most, but not all cases. These data illustrate the importance of conducting engine pumpability tests with fresh, unsheared test oils.

TABLE 10. Used Oil Properties After One Pump Test—LDT-465-1C 15W-40 Oils

Oil No.	1	2	3	4	7	8
Description	OCP	OCP	OCP-L	OCP-H	PMA-L	PMA-H
Oil Properties						
K. Vis, 40°C, cSt						
New	107.47	99.06	101.51	111.86	88.48	97.87
Used	99.78	99.43	86.00	103.40	83.28	94.94
Δ	7.69	0.37	15.51	8.46	5.20	2.93
K. Vis, 100°C, cSt						
New	13.66	13.31	14.90	14.65	15.02	14.58
Used	12.81	13.07	12.72	13.37	13.96	13.98
Δ	0.85	0.24	2.18	1.28	1.06	0.60
BPT, °C						
New	-25.2	-27.3	-27.7	-26.3	-30.1	-28.2
Used	-26.0	-26.3	-28.1	-26.4	-31.0	-27.8
Δ	+0.8	-1.0	+0.4	+0.1	+0.9	-0.4
CCS,* -15°, cp						
New	2900	2830	1950	3400	1950	3300
Used	3400	3300	1850	3150	2100	3200
Δ	+500	+470	-100	-250	+150	-100
CCS, -20°C, cp						
New	7000	ND**	4100	6750	4200	7150
Used	6790		3450	6000	4000	6800
Δ	-10		-650	-750	-200	-350

*Cold cranking simulator
**ND=Not determined

B. GM 6.2L Engine

Low-temperature oil pumpability was investigated in the GM 6.2L engine used to power the U.S. Army HMMWV and CUCV vehicles. All tests were run with the pistons installed and followed the 84CP (slow programmed) cooling cycle. A description of the 6.2L engine is presented in TABLE 11. A schematic of the 6.2L engine lubrication system and the locations of BFLRF oil pressure instrumentation are shown in Fig. 9.(35) Gallery oil

TABLE 11. Engine Specifications for the GM 6.2L Engine

Model:	GM 6.2L
Engine Type:	Four-Cycle, Compression Ignition, Ricardo Comet V Combustion Chamber
Cylinders:	8, V-Configuration
Displacement:	6.217 L (379 cubic inches)
Bore:	10.1 cm (3.98 inches)
Stroke:	9.7 cm (3.82 inches)
Compression Ratio:	21.3:1
Fuel Injection:	Stanadyne DB-2 Fuel Injection Pump, Bosch Pintle Injectors
Rated Power:	116 kW (155 BHP) at 3600 rpm
Rated Torque:	355 NM (262 lb-ft) at 2200 rpm
Idle Speed:	800 rpm (motoring for pumpability tests)

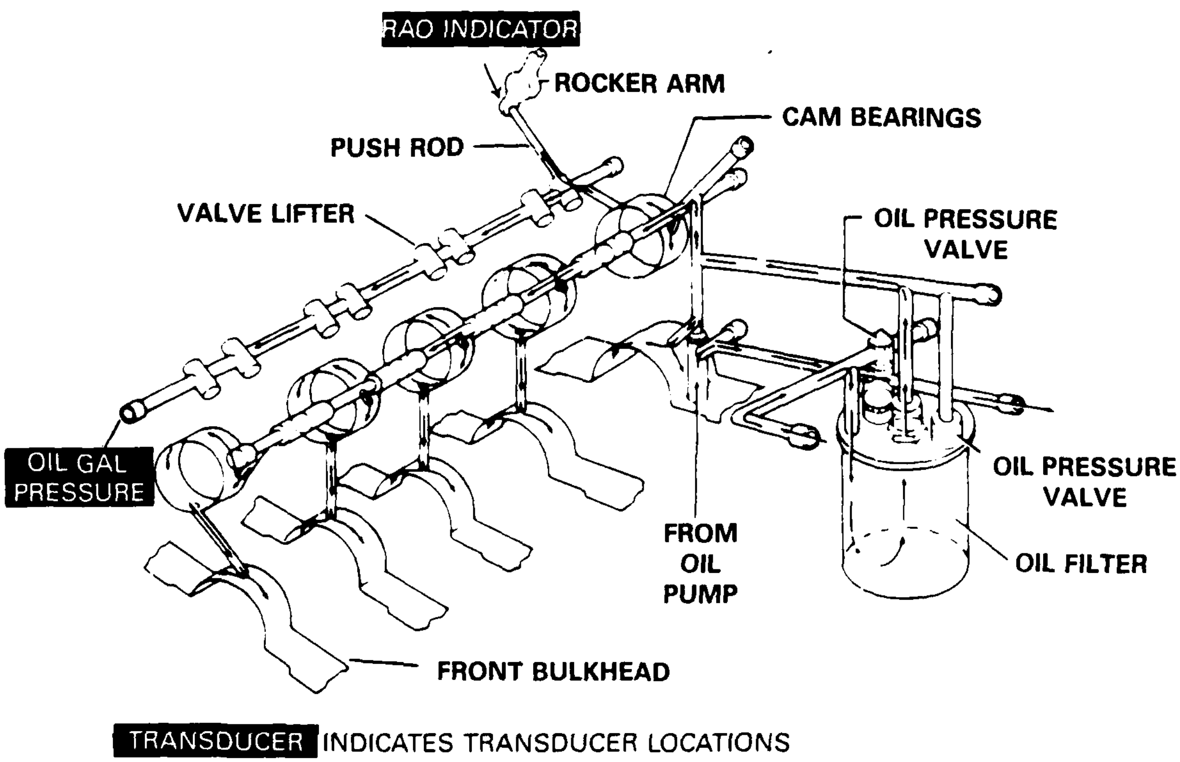


Figure 9. GM 6.2L Engine lubrication system

pressure was measured at the front of the right-hand side valve lifter gallery, the furthest point from the oil pump. Rocker-arm oiling time was determined for this engine at the right rear rocker arm.

Borderline pumping conditions for the 6.2L engine at 800-rpm idle were defined as a minimum oil pressure of 30 psi at 1.0 minute and thereafter. According to the 1984 GMC pickup truck owner's manual, oil pressure at normal operating temperatures with proper engine cooling should be 30-40 psi. If 30 psi is adequate oil pressure during normal operation, it should also be adequate for cold-temperature idle and was selected as the limit. While an oil pressure of less than 30 psi may be acceptable at idle, the oil pressure trace curve is essentially a straight vertical line between 10 and 40 psi, as shown in Fig. 10. This means that the oil BPT as determined by oil pressure at 1.0

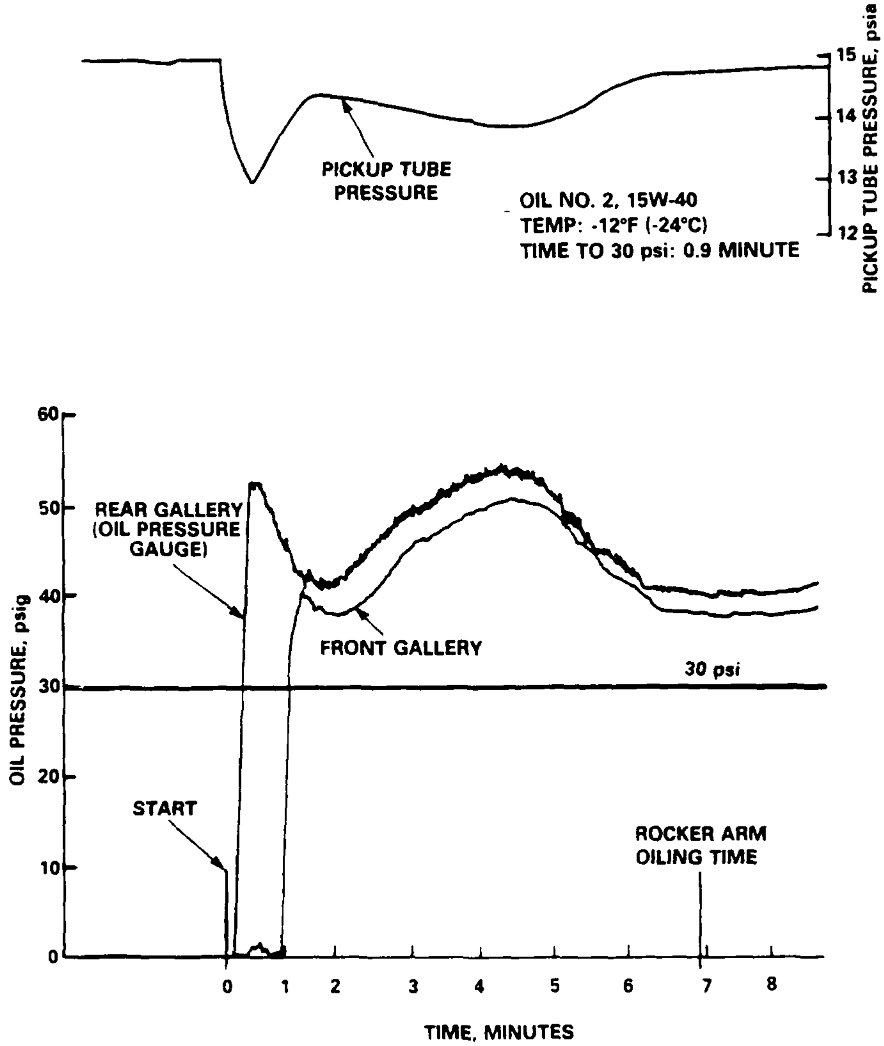


Figure 10. Typical GM 6.2L oil pressure trace

minute would be the same for any oil pressure limit between 10 and 40 psi. The 6.2L engine was generally flow limited at temperatures below the BPT and exhibited some very limited air-binding at temperatures near the BPT, as shown in Fig. 10.

The results of the borderline oil pumpability temperature determinations in the 6.2L engine are presented in TABLE 12. Plots of test temperature versus time to the minimum required oil pressure are provided in Appendix D. In this engine, the most severe 15W-40 oil was Oil No. 5 (special blend SI-H) with a BPT of -9°F (-23°C), while

TABLE 12. Oil Borderline Pumpability Temperature (BPT) in GM 6.2L Engine

Oil No.	Oil Description	BPT, °F(°C)	MRV BPT, °F(°C)	Rocker Arm Oiling Time, minutes
	15W-40 Oils			
1	MIL-L-2104D (OCP)	-12(-24)	-13(-25)	12
2	MIL-L-2104D (OCP)	-17(-27)	-16(-27)	14
3	OCP-L	-16(-27)	-18(-28)	12
4	OCP-H	-11(-24)	-16(-27)	13
5	SI-H	-9(-23)	-15(-26)	13
6	SI-L	-15(-26)	-18(-28)	13
7	PMA-L	NT	-22(-30)	NT
8	PMA-H	NT	-19(-28)	NT
9	Commercial PMA	NT	-20(-29)	NT
10	Commercial SI	-11(-24)	-17(-27)	12
	30 Grade Oils			
11	MIL-L-2104D (75 VI)	+2(-17)	+1(-18)	12
12	MIL-L-2104D	-5(-21)	-8(-22)	12
	Others			
13	10W, MIL-L-2104D	-28(-33)	-29(-34)	13
14	10W-30, OCP-L	-22(-30)	-19(-28)	14
15	5W-30, Synthetic	NT	-26(-32)	NT
16	5W-30, Synthetic	<-22(-30)	<-40(-40)	>14

NT = Not tested.
OCP = Olefin copolymer VII.
SI = Styrene-Isoprene VII.
PMA = Polymethacrylate VII.

Oil No. 11 (75 VI) had the highest BPT of the SAE 30 grades at +2°F (-17°C). The straight-grade 10W had a BPT of -28°F (-33°C). Of particular interest was the rather long rocker-arm oiling times observed for this engine. At borderline pumpability temperature, rocker-arm oiling time was consistently between 12 and 14 minutes. Overall, the BPT, as determined by MRV, was a better predictor of engine-determined BPT in this engine than in the LDT-465-1C engine. Fig. 11 shows a plot of the linear regression of engine-derived BPT on MRV BPT, which had a correlation coefficient (R-squared) of 0.88. The regression analysis summary is presented in TABLE 13. By this analysis, the engine-derived BPTs were approximately 2.5°F higher temperature than the BPT by ASTM D 3829.

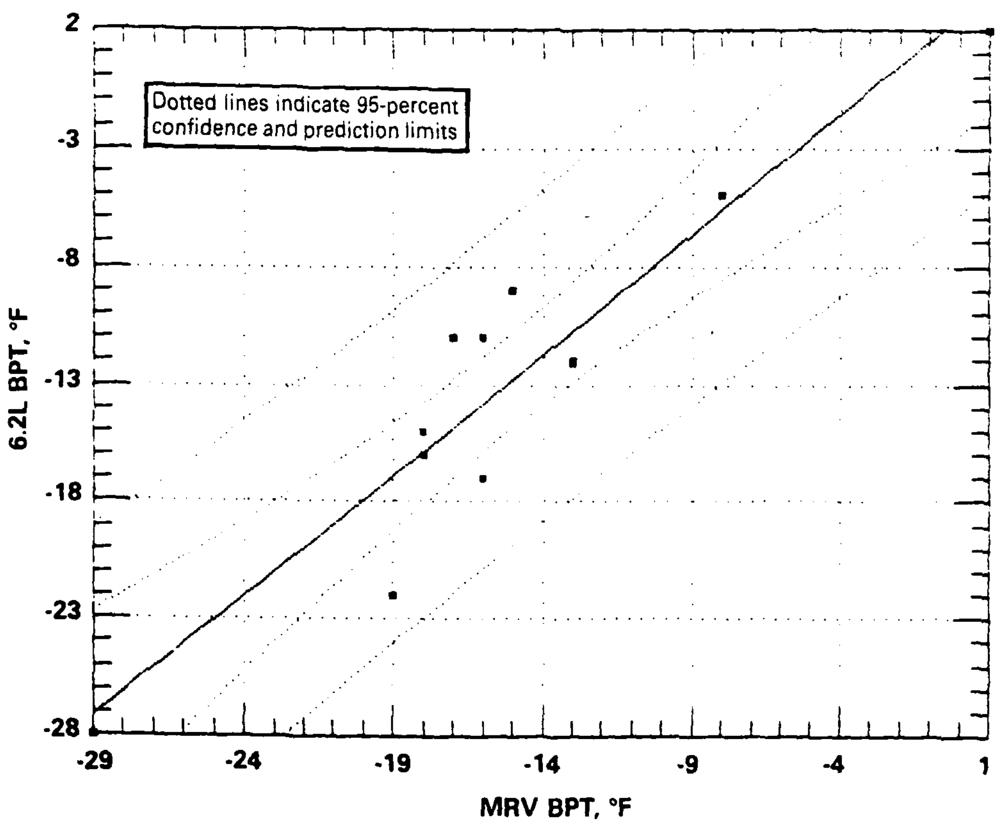


Figure 11. <u>Regression of GM 6.2 BPT on MRV BPT</u>

The used oil kinematic viscosity at 100°C was determined after one pumpability test for the 15W-40 oils tested to determine shear degradation of the oils. As shown in TABLE 14, viscosity loss at 100°C ranged from 0.5 to 1.5 cSt after one pumping test,

TABLE 13. BPT Regression Analysis—GM 6.2L Engine

Regression Analysis - Linear model: Y = a+bX
Dependent variable: DD62BPT

Independent variable: MRVBPT

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	2.53391	2.14021	1.18396	0.266756
Slope	1.02305	0.127284	8.03759	2.13206E-5

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	569.56195	1	569.56195	64.60292	0.00002
Error	79.347143	9	8.816349		
Total (Corr.)	648.90909	10			

Correlation Coefficient = 0.936868

R-squared = 0.88

Std. Error of Est. = 2.96923

TABLE 14. Used Oil Viscosity of 15W-40 Oils After One Pump Test—GM 6.2L Engine

Oil No.	Description	K. Vis, 100°C, cSt		
		New	Used	Loss
1	OCP	13.66	12.75	0.91
2	OCP	13.31	12.85	0.46
3	OCP-L	14.90	13.38	1.52
4	OCP-H	14.65	13.12	1.53
6	SI-L	14.51	13.63	0.88
7	SI-H	13.97	13.62	0.35

which was very similar to the observed viscosity loss in the LDT-465-1C engine. Overall, the 6.2L diesel engine was less severe than the LDT-465-1C with respect to low-temperature oil pumpability.

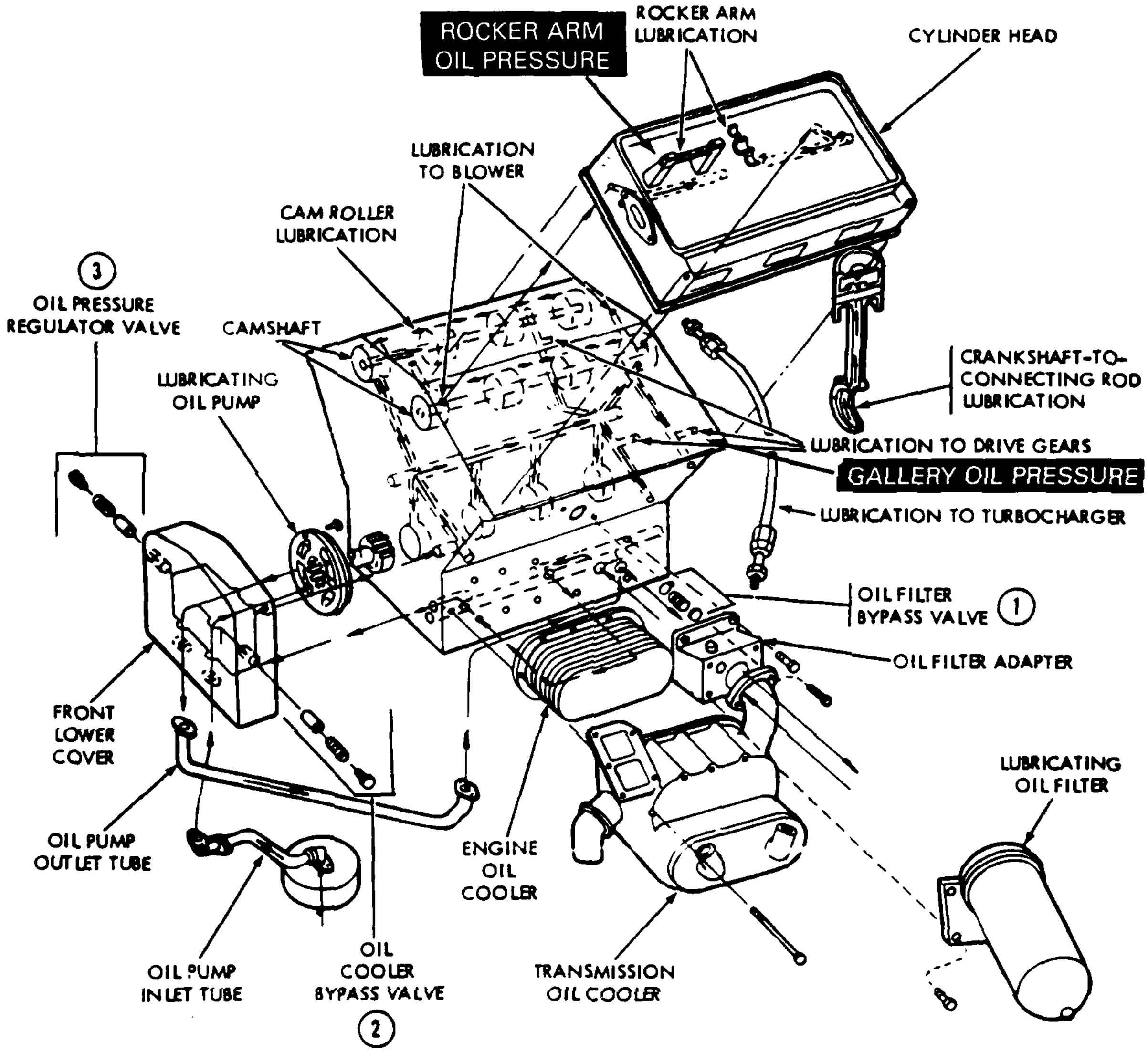
C. DDC 6V-53T Engine

The next engine to be investigated for low-temperature oil pumpability was the DDC 6V-53T, which is representative of a two-cycle diesel engine series used to power many of the U.S. Army combat vehicles. For all tests, the slow-cooling procedure (84CP) was used, and pistons were installed. A description of the DDC 6V-53T engine is presented in TABLE 15. Fig. 12 contains a schematic of the engine lubricating system with the locations of the oil pressure pickups used in the tests.(36) Gallery oil pressure was obtained from the left rear main oil gallery; turbocharger oil pressure was obtained from the oil line feeding it; and rocker-arm oil pressure was obtained from the right front cylinder (1R).

TABLE 15. Engine Specifications for the DDC 6V-53T Engine

Model:	5063-5395
Engine Type:	Two-Cycle, Compression Ignition, Direct Injection, Turbo-supercharged
Cylinders:	6, V-Configuration
Displacement:	5.21 L (318 cubic inches)
Bore:	9.8 cm (3.875 inches)
Stroke:	11.4 cm (4.5 inches)
Compression Ratio:	18.7:1
Fuel Injection:	DD Unit Injectors, N-70
Rated Power:	224 kW (300 BHP) at 2800 rpm
Rated Torque:	858 NM (633 lb-ft) at 2200 rpm
Idle Speed:	600 rpm (motoring for *pumpability tests*)

Borderline oil-pumping conditions for the 6V-53T engine at 600 rpm idle were defined as a minimum turbocharger oil pressure of 30 psi at 1.0 minute and thereafter. The 6V-53T oil qualification test procedure has an oil-pressure limit of 30 psi at operating speeds and temperatures.(37) The same 30-psi limit was selected for this program to provide a margin of safety at cold idle conditions. As with the 6.2L engine, the oil pressure trace for the 6V-53T engine is nearly a vertical line between initial pumping and 50 psi; thus, the BPT as determined by minimum oil pressure at 1.0 minute would be nearly the same for any oil pressure limit between 5 and 50 psi. A typical oil pressure trace for a pumpability test is shown in Fig. 13. In the 6V-53T, at BPT conditions, the gallery had almost immediate oil pressure, while pressure to the turbocharger developed slightly later. Air binding was observed in the gallery pressure trace and, to a lesser extent, in the turbocharger trace at BPT conditions. A sudden spike of loss in turbocharger oil pressure, followed by an immediate recovery in oil pressure, was a typical oil-pumpability characteristic of this engine at low temperatures.



NOTES

1. OIL FILTER BYPASS VALVE OPENS AT 12 PSI.
2. OIL COOLER BYPASS VALVE OPENS AT 30 PSI.
3. OIL PRESSURE REGULATOR VALVE OPENS AT 51 PSI.

TRANSDUCER INDICATES TRANSDUCER LOCATIONS

Figure 12. Lubricating system diagram for DDC 6V-53T engine

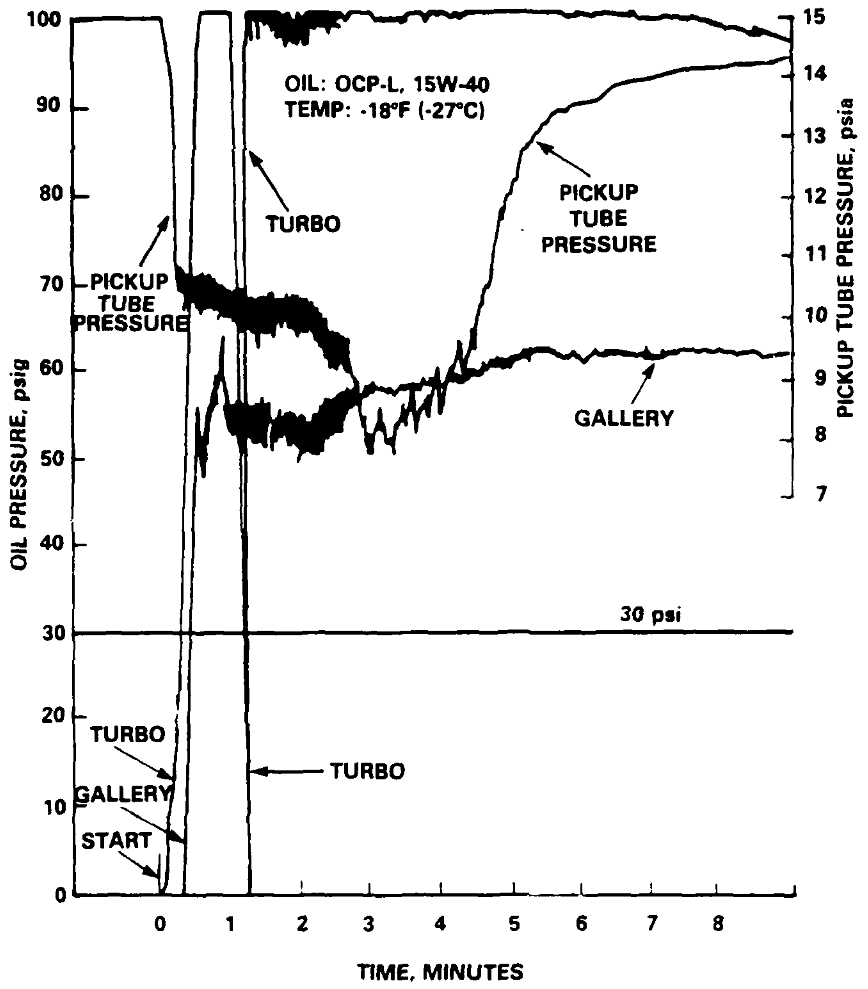


Figure 13. Typical pressure trace for DDC 6V-53T engine

The results of the oil pumpability tests in the 6V-53T engine are presented in TABLE 16. Plots of test temperature versus time to the minimum required idle oil pressure are in Appendix E. In this engine, the most severe 15W-40 oil was Oil No. 1 (OCP) with a BPT of -11°F (24°C), vhile Oil No. 11 (75 VI) (an SAE 30 grade) had the highest BPT at +1°F (-17°C). The SAE 10W grade (Oil No. 13) is not recommended for use in this engine series; however, it was evaluated for information only and found to have a BPT of -30°F (-34°C). Rocker-arm oiling times at BPT conditions were between 2 and 3 minutes for most of the oils. Fig. 14 shows a plot of the linear regression of engine-derived BPT on the BPT from the MRV. The correlation coefficient (R-squared) for this regression was only 0.61 (TABLE 17). The 6V-53T engine has a very powerful oil pump,

TABLE 16. Oil Borderline Pumpability Temperature (BPT) in DDC 6V-53T Engine

Oil No.	Oil Description	BPT °F(°C)	MRV BPT, °F(°C)	Rocker-Arm Oiling Time, minutes	Pour Point, °F(°C)
	15W-40 Oils				
1	MIL-L-2104D (OCP)	-11(-24)	-13(-25)	2.0	-11(-24)
2	MIL-L-2104D	-16(-27)	-16(-27)	2.8	-15(-26)
3	OCP-L	-16(-27)	-18(-28)	2.5	-17(-27)
4	OCP-H	-13(-25)	-16(-27)	2.4	-17(-27)
5	SI-H	-21(-29)	-15(-26)	3.7	-9(-23)
6	SI-L	-19(-28)	-18(-28)	2.4	-13(-25)
7	PMA-L	-24(-31)	-28(-33)	3.0	-18(-28)
8	PMA-H	-21(-29)	-19(-28)	3.5	-18(-28)
9	Commercial PMA	-24(-31)	-22(-30)	3.8	-27(-33)
10	Commercial SI	-20(-29)	-17(-27)	3.0	-11(-24)
	30-Grade Oils				
11	MIL-L-2104D (75 VI)	-13(-25)	-1(-17)	4.0	-6(-21)
12	MIL-L-2104D	-15(-26)	-8(-22)	2.8	-11(-24)
	Others				
13	10W, MIL-L-2104D	-30(-34)	-29(-34)	3.1	-27(-33)
14	10W-30, OCP-L	NT	-19(-28)	NT	ND
15	5W-30, Synthetic	NT	-26(-32)	NT	ND
16	5W-30, Synthetic	< -30(-34)	< -40(-40)	ND	ND

NT = Not tested.
OCP = Olefin copolymer VII.
SI = Styrene-Isoprene VII.
PMA = Polymethacrylate VII.
ND = Not determined.

as it was able to pump oils through the system at temperatures near or below their pour point where the oils are a semisolid slush. For example, Oil No. 11 (75 VI SAE 30 grade) had a pour point of -6°F (-21°F), and an engine-derived BPT of -13°F (-25°C). Pour point was examined as a predictor of engine-derived BPT as shown in the linear regression analysis in TABLE 18 and plotted in Fig. 15. The correlation coefficient (R-squared) of 0.48 revealed no strong relationship between pour point and the BPT in the 6V-53T engine.

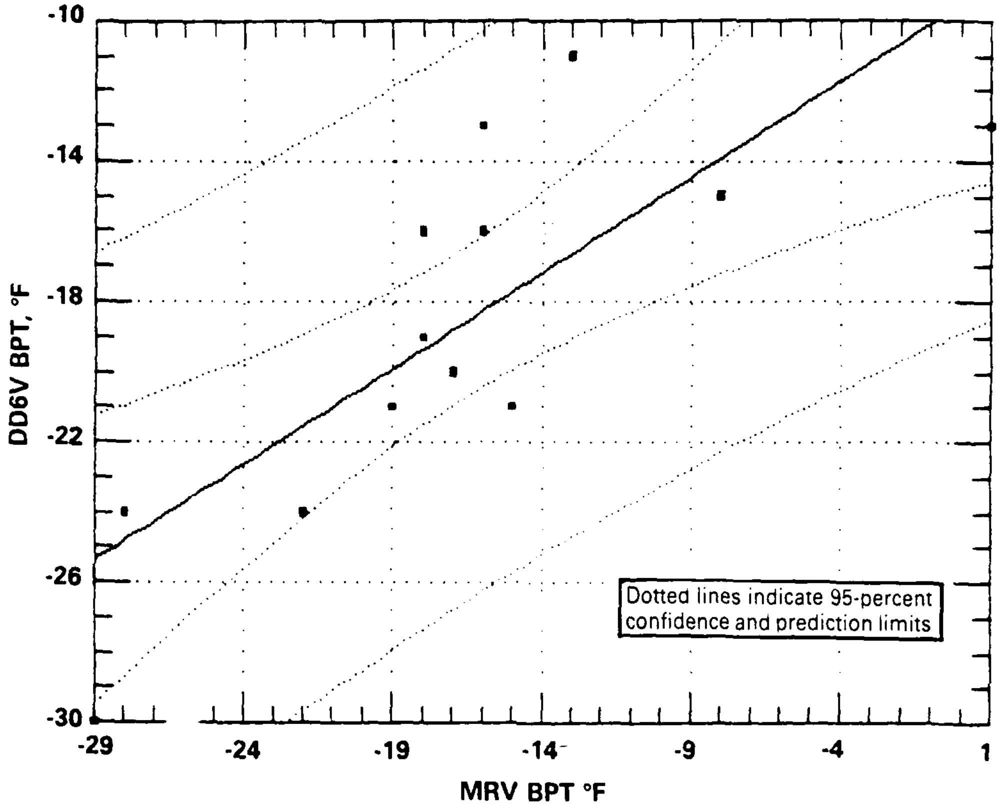


Figure 14. Regression of DDC6V BPT on MRV BPT

The used oil kinematic viscosity at 100°C was determined for the 15W-40 oils after one 6V-53T pumpability test to determine shear degradation of the oils (TABLE 19). The observed viscosity loss ranged from 0.23 to 1.74 centistokes, which was very similar to the loss observed in the LDT-465-1C and GM 6.2L engines. Overall, the 6V-53T engine was less severe with respect to low-temperature oil pumpability than either the LDT-465-1C or GM 6.2L engines.

TABLE 17. BPT Regression Analysis—DDC 6V-53T Engine

Regression Analysis - Linear model: Y = a+bX
Dependent variable: DD6VBPT   Independent variable: BPT

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-9.56656	2.39082	-4.00136	2.08133E-3
Slope	0.544196	0.130281	4.17709	1.54412E-3

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	213.91087	1	213.91087	17.44808	0.00154
Error	134.85836	11	12.25985		
Total (Corr.)	348.76923	12			

Correlation Coefficient = 0.783154   R-squared = 0.61
Std. Error of Est. = 3.50141

TABLE 18. Engine BPT Regression Analysis on Pour Point

Regression Analysis - Linear model: Y = a+bX
Dependent variable: DD6VBPT   Independent variable: POURPT

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-9.65686	3.07507	-3.14037	9.40248E-3
Slope	0.587304	0.185876	3.15965	9.08487E-3

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	165.93600	1	165.93600	9.98339	0.00908
Error	182.83323	11	16.62120		
Total (Corr.)	348.76923	12			

Correlation Coefficient = 0.689765   R-squared = 0.48
Std. Error of Est. = 4.07691

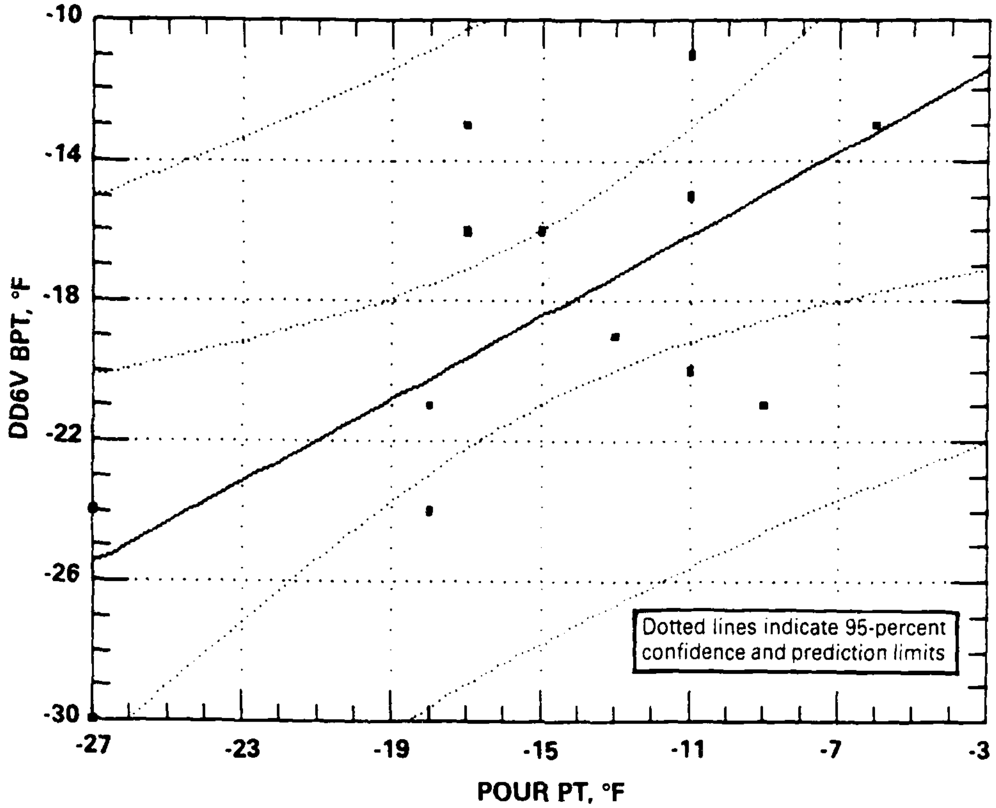


Figure 15. Regression of DDC6V BPT on pour point

Table 19. Used Oil Viscosity of 15W-40 Oils After One Pump Test--DDC 6V-53T Engine

Oil No.	Description	K. Vis, 100°C, cSt New	Used	Loss
1	OCP	13.66	12.67	0.99
2	OCP	13.31	12.68	0.63
3	OCP-L	14.90	13.16	1.74
4	OCP-H	14.65	13.17	1.48
6	SI-L	14.51	14.26	0.25
5	SI-H	13.97	13.80	0.17
7	PMA-L	15.02	13.76	1.26
8	PMA-H	14.58	13.70	0.88
10	Comm. SI	14.34	14.11	0.23
9	Comm. PMA	14.20	13.49	0.71

D. Cummins VTA-903T Engine

The final engine to be investigated for low-temperature oil pumpability was the Cummins VTA-903T engine used to power U.S. Army M2 and M3 combat vehicles. All tests were run following the slow cooling procedure (84CP) with the pistons installed. TABLE 20 contains a description of the VTA-903T engine, while Fig. 16 is a block diagram of the engine lubrication system.(38) Gallery oil pressure was measured at the right rear of the engine block while turbocharger oil pressure was measured at the

TABLE 20. Engine Specifications for the Cummins VTA-903T Engine

Model:	VTA-903T
Engine Type:	Four-Cycle, Compression Ignition, Direct Injection
Cylinders:	8, V-Configuration
Displacement:	14.8 L (903 cubic inches)
Bore:	14.0 cm (5.5 inches)
Stroke:	12.1 cm (4.75 inches)
Compression Ratio:	15.5:1
Fuel Injection:	Cummins PT
Rated Power:	373 kW (500 BHP) at 2600 rpm
Rated Torque:	1369 NM (1010 lb-ft) at 2400 rpm
Idle Speed:	800 rpm (motoring for pumpability tests)

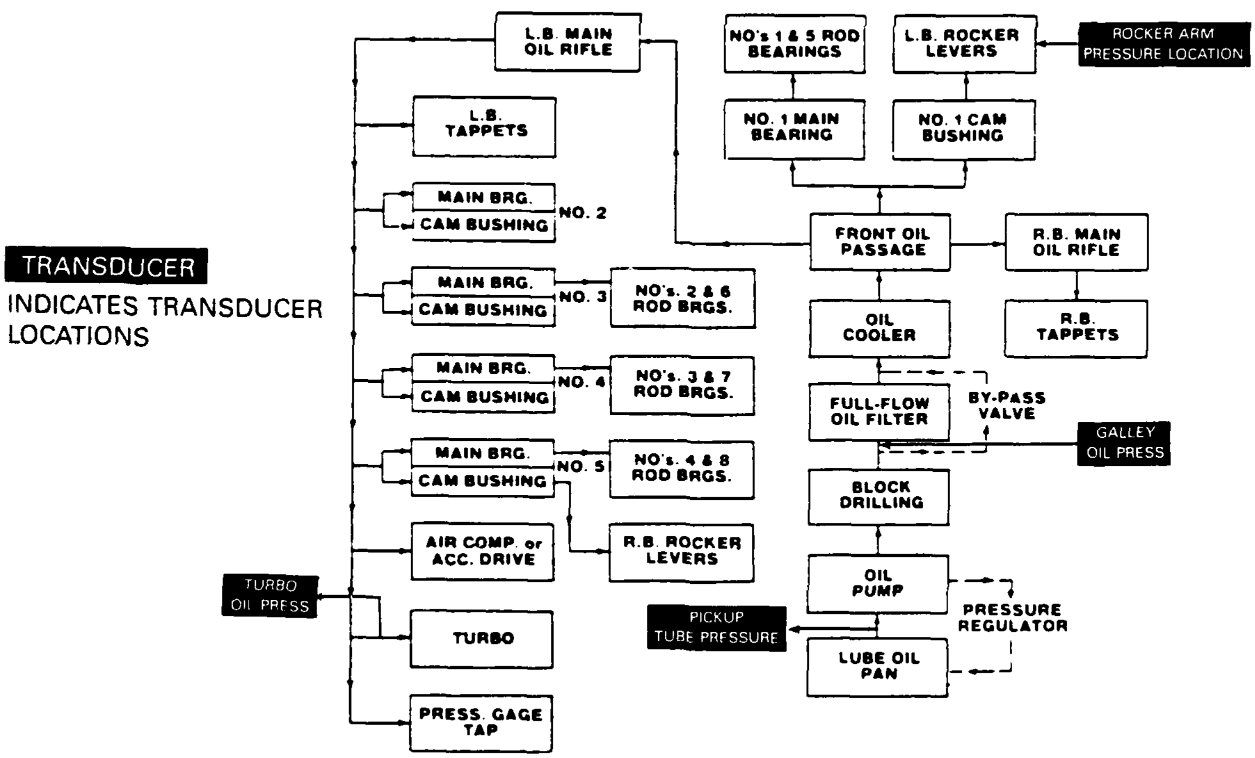


Figure 16. Cummins VTA-903T engine oil flow diagram

oil delivery line leading to the turbocharger. Rocker-arm oil pressure was measured at left front of the engine (cylinder No. 5).

Borderline oil-pumping conditions for the VTA-903T engine at 800-rpm idle were defined as a minimum turbocharger oil pressure of 10 psi at 1.0 minute and thereafter.(38) As observed in other engines, the turbocharger oil-pressure trace was nearly a straight vertical line from initial pressure development to 30 psi; thus, the BPT determined at 1.0 minute would be nearly the same for any pressure limit between 1 and 30 psi. A typical oil pressure trace for this engine at borderline pumping conditions is shown in Fig. 17. The VTA-903T engine had the following general oil pumpability characteristics:

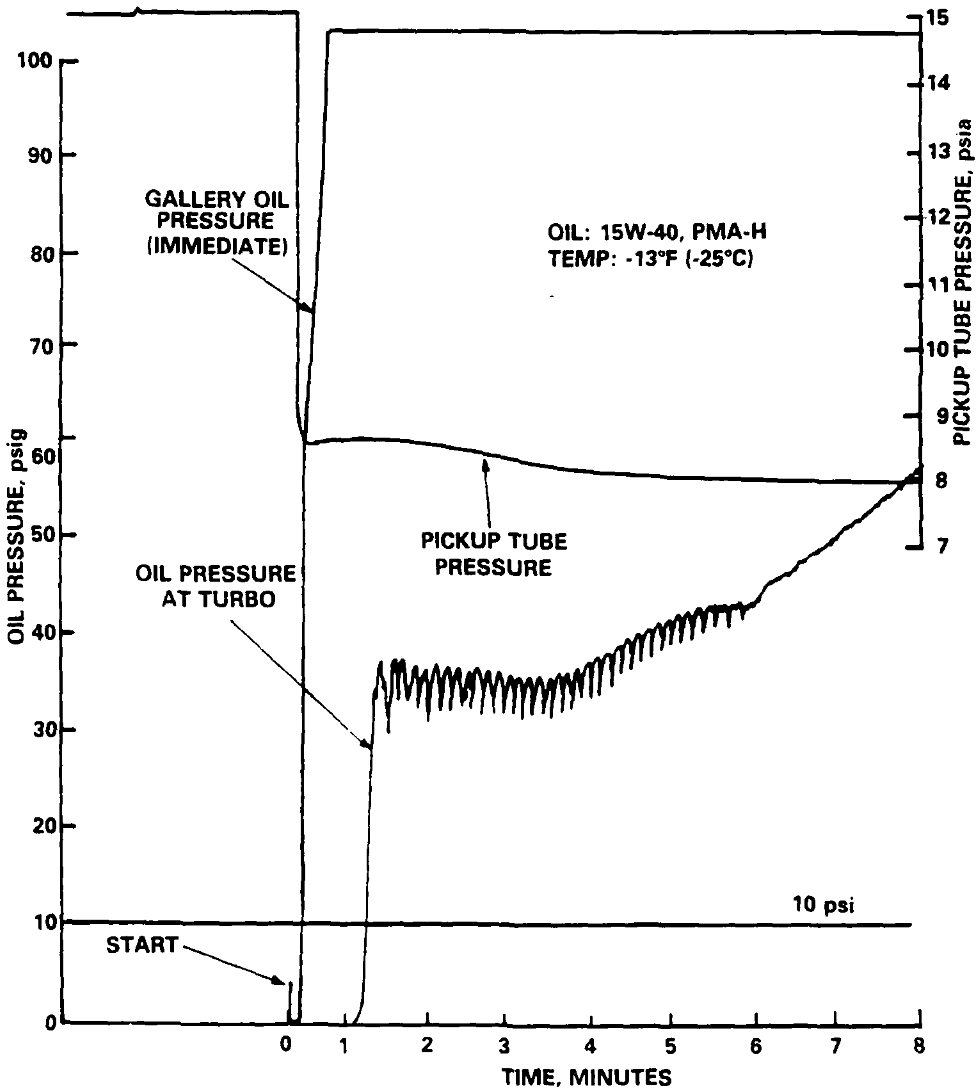


Figure 17. Typical oil pressure trace for VTA-903T engine

at a given temperature, oil pressure developed at the turbocharger after gallery pressure; at BPT gallery, oil pressure was immediate and turbocharger oil pressure showed indications of air binding. In fact, gallery oil pressure developed immediately for all test conditions examined. For example, using SAE 10W grade oil at -38°F (-39°C) resulted in immediate gallery oil pressure, while turbocharger oil pressure took in excess of 15 minutes to develop. At BPT, it generally took 3.5 to 4.5 minutes to develop 1.0 psi rocker-arm oil pressure. The BPTs determined in the VTA-903T engine are presented in TABLE 21. Appendix F contains plots of test temperature versus time to minimum required idle oil pressure. Special 15W-40 blend OCP-H (Oil No. 4) was the most severe 15W-40 oil with a BPT of -6°F (-21°C). As observed in the other engines, the 15W-40 oils formulated with PMA-VII had the lowest BPTs. Oil No. 11 (75 VI SAE 30-grade) had the highest BPT at +7°F (-14°C). BPT of the SAE 10W grade was -21°F (-29°C), while the synthetic 5W-40 product had a BPT of -35°F (-37°C). At BPT conditions, rocker-arm oiling times were between 3.5 and 4.5 minutes. Fig. 18 shows a plot of the linear regression of engine-derived BPT on BPT from the MRV (ASTM D 3829). The correlation coefficient (R-squared) for this regression was 0.76 as shown in TABLE 22. Overall, the VTA-903T engine was similar in low-temperature oil pumpability severity to the LDT-465-1C engine. These two engines were the most severe (highest BPTs) of the four engines investigated.

TABLE 21. Oil Borderline Pumpability Temperature (BPT) in Cummins VTA-903 Engine

Oil No.	Oil Description	BPT, °F(°C)	MRV BPT, °F(°C)	Rocker-Arm Oiling Time, minutes
	15W-40 Oils			
1	MIL-L-2104D (OCP)	-7(-22)	-13(-25)	4.0
2	MIL-L-2104D (OCP)	-9(-23)	-16(-27)	ND
3	OCP-L	-10(-23)	-18(-28)	4.5
4	OCP-H	-6(-21)	-16(-27)	3.5
5	SI-H	-9(-23)	-15(-26)	3.8
6	SI-L	NT	-18(-28)	NT
7	PMA-L	-18(-28)	-22(-30)	4.3
8	PMA-H	-13(-25)	-19(-28)	4.4
9	Commercial PMA	-14(-26)	-20(-29)	3.8
10	Commercial SI	NT	-17(-27)	NT
	30 Grade Oils			
11	MIL-L-2104D (75 VI)	+7(-14)	+1(-17)	3.6
12	MIL-L-2104D	-4(-20)	-8(-22)	4.3
	Others			
13	10W, MIL-L-2104D	-21(-29)	-29(-34)	4.2
14	10W-30, OCP-L	-18(-28)	-19(-28)	4.1
15	5W-30, Synthetic	-38(-39)	-26(-32)	3.1
16	5W-30, Synthetic	-38(-39)	< -40(-40)	4.0
17	5W-40, Synthetic	-35(-37)	< -40(-40)	3.7

NT = Not tested.
OCP = Olefin copolymer VII.
SI = Styrene-Isoprene VII.
PMA = Polymethacrylate VII.
ND = Not determined.

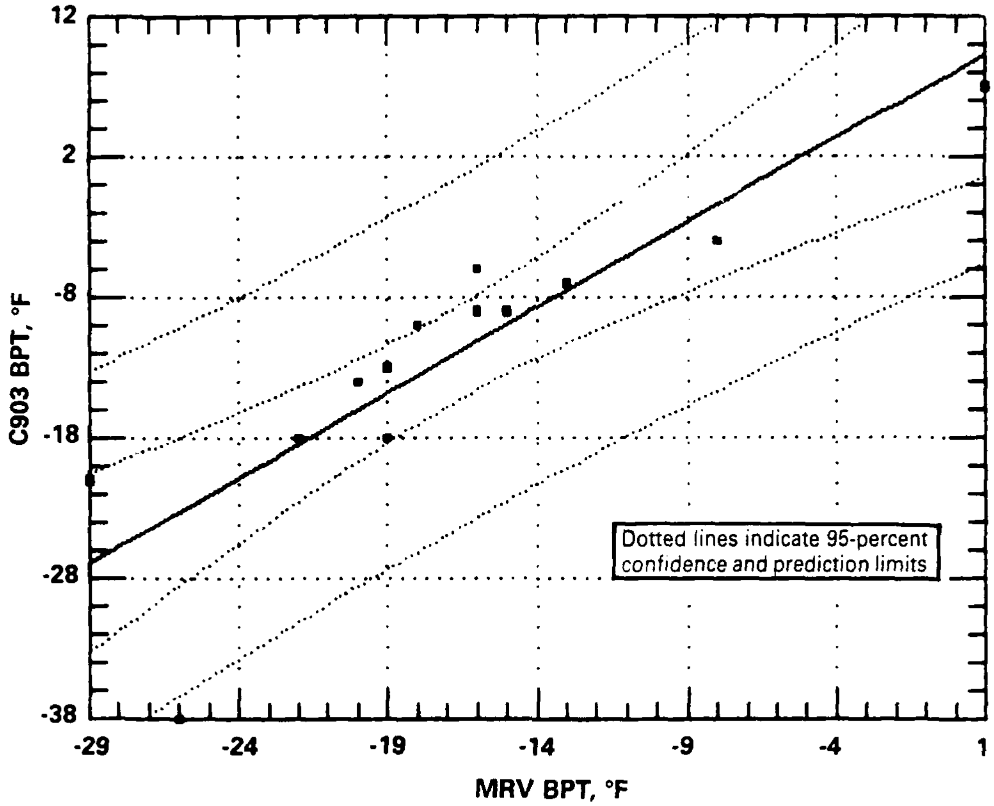


Figure 18. Regression of C903 BPT on MRV BPT

TABLE 22. BPT Regression Analysis—VTA-903T Engine

Regression Analysis - Linear model: Y = a+bX

Dependent variable: C903BPT

Independent variable: BPTF

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	8.1315	3.81331	2.1324	0.0563444
Slope	1.20777	0.206853	5.8388	1.12715E-4

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	1013.6912	1	1013.6912	34.0916	0.00011
Error	327.07804	11	29.73437		
Total (Corr.)	1340.7692	12			

Correlation Coefficient = 0.869512

R-squared = 0.76

Std. Error of Est. = 5.45292

E. Summary

Borderline oil-pumpability temperatures (BPTs) were determined by engine cranking experiments conducted in a cold box. The variables investigated included: four different engine types; four different oil viscosity grades; and three different viscosity index improver chemistries. Fig. 19 shows the limiting BPTs for each engine grouped by oil viscosity class. In general, for a given oil, the decreasing order of engine severity (i.e., highest BPT) was: the LDT-465-1C and the VTA-903T were the most severe and were approximately equivalent. The GM 6.2L engine was the next least severe, and the DDC 6V-53T engine was the overall least severe. Note that the 6V-53T engine tended to

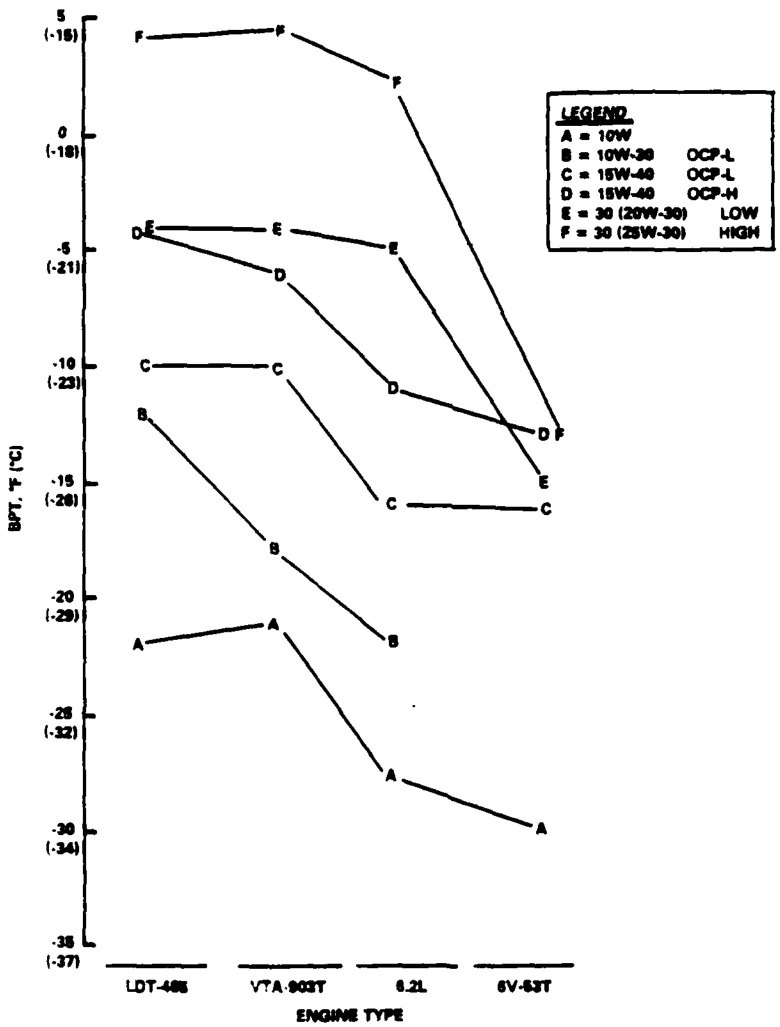


Figure 19. BPT ranges for viscosity classes by engine type

group all the 15W-40 and 30-grade oils between -13° (-25°) and -16°F (-27°C) due to its very strong oil pump.

TABLE 23 contains the engine-derived BPTs for the special blend 15W-40 oils that were formulated to the upper and lower 15W specification limits. The different VII chemistries of the special blend test oils included: olefin copolymer (OCP), styrene-isoprene polymer (SI), and polymethacrylate (PMA). The PMA-containing 15W-40 oils had superior low-temperature oil pumpability performance in each engine in which they were evaluated. Oils formulated with SI VII had similar to slightly better low-temperature pumpability performance than the OCP-containing oils. TABLE 24 contains a summary of the limiting engine-derived BPTs for the engine/oil matrix. The limiting BPT for each oil type is boxed in TABLE 24. For 15W-40 grade oils, the most severe condition was an oil formulated with OCP VII operated in the LDT-465-1C engine. For the SAE 30 grade oils, the 75 VI product was limiting in the VTA-903T engine. This same engine was limiting for the single SAE 10W grade oil investigated.

TABLE 23. BPTs of Special Blend 15W-40s

Oil No.	Description	BPT, °F(°C) VTA-903T	DDC6V-53T	GM 6.2L	LDT-465-1C
3	OCP-L	-10(-23)	-16(-27)	-16(-27)	-10(-23)
6	SI-L	NT	-19(-28)	-15(-26)	NT
7	PMA-L	-18(-28)	-24(-31)	NT	-20(-29)
4	OCP-H	-6(-21)	-13(-25)	-11(-24)	-4(-22)
5	SI-H	-9(-23)	-21(-29)	-9(-23)	NT
8	PMA-H	-13(-25)	-21(-29)	NT	-17(-27)

NT = Not tested.

The BPT range (R) for a given VII type and engine is defined as the engine-derived BPT for the oil blended to the upper limits of the viscosity grade (BPT_{UL}) less the engine-derived BPT of the oil blended to the lower limit of the grade (BPT_{LL}). The equation is: $R = BPT_{UL} - BPT_{LL}$.

TABLE 24. Summarized Results: Limiting BPTs

	Temperature, °F(°C)			
	LDT-465-1-C	GM 6.2 L	DDC 6V-53T	VTA-903T
15W-40				
OCP	$\boxed{-4(-20)}$	-11(-24)	-11(-24)	- 6(-21)
PMA	-17(-27)	NT	-21(-29)	$\boxed{-13(-25)}$
SI	$\boxed{-8(-22)}$	-11(-24)	-19(-28)	- 9(-23)
30				
95 VI	$\boxed{-4(-20)}$	- 5(-21)	-15(-26)	$\boxed{-4(-20)}$
75 VI	+ 6(-14)	+ 2(-17)	-13(-25)	$\boxed{+7(-14)}$
10 W	-22(-30)	-28(-33)	-30(-34)	$\boxed{-21(-29)}$
5W-30	$\boxed{-33(-36)}$	<-22(-30)	<-30(-34)	-38(-39)
5W-40	NT	NT	NT	-35(-37)

$\boxed{}$ = Limiting value for this oil type
NT = Not Tested

TABLE 25 shows the range of engine-derived BPTs for 15W-40 oils grouped by engine type and VII chemistry. For oils blended with OCP VII to the lower and upper 15W-40 viscosity limits, the BPTs in the LDT-465-1C engine increased by 6°F over the 15W-40 viscosity grade. The 15W-40 BPT ranges varied from 2° to 6°F, with no consistent trends with respect to VII chemical type or engine type.

TABLE 25. Range of BPTs Within 15W-40 Oil Class

	Temperature Range, °F			
Engine Type VII Chemistry	LDT-465-1C	GM 6.2L	DDC 6V-53T	VTA-903T
OCP	6	6	5	4
PMA	3	ND*	3	5
SI	ND	6	2	ND

*ND = Not Determined

The BPTs determined by ASTM D 3829 did not completely predict engine-derived BPTs. The linear regression correlation coefficients (R-squared) resulting from the two different BPT values ranged from 0.61 to 0.88.

The shear effects of a single pumpability test for three engine types are summarized in TABLE 26 for 15W-40 oils. Each engine produced approximately the same viscosity shear loss. Of the particular VII additives represented, the SI material experienced the least viscosity shear loss. The shear data apply to these particular oils only, and should not be extrapolated or generalized to other oils of the same VII chemistry.

TABLE 26. Shear Effects for One Pumpability Test

Oil No.	Description	K. Vis Loss at 100°C, cSt (15W-40 Oils) LDT-465-1C	GM 6.2L	DDC 6V-53T
1	MIL-L-2104D (OCP)	0.85	0.91	0.99
3	OCP-L	2.18	1.52	1.74
4	OCP-H	1.28	1.53	1.48
7	PMA-L	1.06	1.26	ND*
8	PMA-H	0.60	0.88	ND
6	SI-L	ND	0.88	0.25
5	SI-H	ND	0.35	0.17

*ND = Not Determined

V. CONCLUSIONS

The following conclusions are made based on the results of the low-temperature oil pumpability tests:

- Each engine had a unique set of low-temperature oil pumpability characteristics. The LDT-465-1C and the VTA-903T engines were the most severe in terms of low-temperature oil pumpability performance, i.e., they required a higher temperature for a given oil to pump adequately. The GM 6.2L engine was the next least severe, while the DDC 6V-53T engine was the overall least severe. The 6V-53T engine was able to pump oils at temperatures below their pour point.

- The limiting engine-derived BPTs for various viscosity grades were as follows:

  for 15W-40s, the limiting BPT was -4°F (-20°C),
  for SAE 30 grade, the limiting BPT was +7°F (-14°C),
  and for SAE 10W grade, the limiting BPT was -21°F (-29°C)

- The PMA-containing 15W-40 oils had superior low-temperature oil pumpability performance in each engine in which they were evaluated.

- The 15W-40 oils formulated with SI VII had similar to slightly better low-temperature pumpability performance than the OCP-containing oils.

- The BPTs determined by ASTM D 3829 (MRV) did not adequately predict engine-derived BPTs. The linear regression correlation coefficients (R-squared) resulting from the two different BPT values ranged from 0.61 to 0.88, and the data had rather large confidence bands.

- Each engine produced approximately the same viscosity shear loss during a single pumpability test. Of the particular VII additives represented, the SI material experienced the least viscosity shear loss. The shear data apply to these particular oils only, and should not be extrapolated or generalized to other oils of the same VII chemistry.

VI. RECOMMENDATIONS

The following recommendations for low-temperature use limits for U.S. Army diesel-powered ground vehicles are offered based on the BPTs developed during this program. Low-temperature use limits were defined as +5°F warmer than the highest engine-derived BPT. The 5°F was added to the BPT to provide a margin of safety. It is recommended that the low-temperature use limit for MIL-L-2104D grade 15W-40 can be safely lowered to 0°F (-18°C), and the use limit for SAE grade 30 can be safely lowered to +10°F (-12°C). It is recommended that the grade 10W low-temperature use limit of -15°F (-26°C) be retained.

Additional research is recommended since BPTs from ASTM D 3829 do not adequately predict BPTs from heavy-duty diesel engines. A mathematical model needs to be developed that could be used to predict the expected BPT of any diesel engine/lubricant combination that the Army might encounter. Variables such as engine geometry (oil pickup tube length and diameter, main oil gallery dimensions etc), engine hardware characteristics such as oil pump flow rate and engine oil properties would form the basis for this predictive model. Once the preliminary model is formed based on the currently available engine-derived BPTs, the critical engine geometries and characteristics of other available diesel engines should be considered. If any engines are identified that have geometric or flow properties that fall outside the range of the engines used in the current program, additional low-temperature engine pumpability determinations would be recommended.

Finally, low-temperature oil pumpability requirements should be determined for other vehicle components such as powershift transmissions and power steering units. The effects of operation at low-temperature, high-viscosity conditions should be determined for gearboxes, transmissions, and other vehicle components that do not pump their lubricant.

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APPENDIX A

Test Cell Configuration

A. Cold-Box Description

A refrigerated box was used to cool the test engines to the desired test temperatures. The cold box initially used in the program employed a 3-horsepower electrically powered single-stage compressor and was capable of attaining temperatures as low as -35°F (-37°C). The test engine was bolted to a bedplate and the cold box assembled around it. A sheet of polyethylene film was then cut and taped to the bedplate to act as a vapor barrier. Next, a 2-inch (5-cm) layer of polystyrene foam was cut and placed on the floor to serve as an insulator. Lastly, another layer of polyethylene film was taped down to act as a spill retainer and additional vapor barrier. The refrigeration equipment was controlled in a on-off mode using a Honeywell UDC-500 controller and a Honeywell DPC-7700 set point programmer. The box, which was equipped with a 4-foot wide access door, was able to attain test temperatures as low as -35°F (-37°C) and maintain them ± 2°F.

A second refrigerated box was used later in the program. This box had a 5-horsepower dual-stage compressor and was capable of attaining test temperatures as low as -40°F (-40°C). This box had one completely removable wall that facilitated the changeout of engines without disassembly of the entire box. The floor of this box was insulated in the same manner as the other. Changeout of the box revealed that moisture had migrated through the vapor barrier and into the bedplate foundation. This moisture caused extensive rusting of the bedplate and deterioration of the foundation due to freeze-thaw effects. When the second box was installed, great care was taken to seal the vapor barriers better and fit the insulation to the bedplate. In addition, insulation was placed on the support legs of the test engine to minimize heat infiltration into the cold box and minimize sweating of the baseplate.

B. Engine Cranking System

Initially a 50-horsepower motoring dynamometer was used to motor the test engines at the desired speeds. This system proved to be difficult to use since the torque available at low speeds (800 to 1000 rpm) was very limited. The dynamometer control system tended to blow fuses at these low cranking speeds. As a result of this problem, and a fuel-dribble problem, discussed later, the pistons and connecting rods were removed from the first test engine (the Continental LDT-465-1C). After this initial attempt, a special cranking system was designed to provide reliable and repeatable motoring of the test engine. This design consisted of a driving engine, a clutch, a 12-speed truck transmission, and a driveshaft connecting the transmission to the test engine. The driving engine was initially a Cummins NTC-350 diesel engine. The clutch on the transmission was actuated with an air cylinder such that air pressure was required to disengage the clutch. A needle valve was used to control the air bleed from the cylinder and thus control the engagement of the clutch. The driving and driven engines were placed back-to-back and the transmission operated in high-range reverse. The speed of the driven engine was controlled by an air cylinder on its rack. The driveshaft between the transmission and the test engine passed through a hole in the side of the cold box. Although the passthrough was insulated with rubber curtains on the inside and outside surfaces of the cold box, the passthrough was an unavoidable source of moisture and heat intrusion into the cold box. During the test program, it became necessary to change the driving engine to a Detroit Diesel 6V-53T engine because the Cummins NTC-350 engine was needed for another test program. The change had little or no impact on the test since both engines were capable of providing the same range of test speeds. Later in the program, the Cummins NTC-350 engine was reinstalled as the driving engine. Test speeds of 175 to 1000 rpm were possible using this cranking apparatus. Speeds lower than 150 rpm caused excessive torsional vibrations in the driveshaft and were avoided by running the driving engine higher than these rpm's before engaging the clutch. The driving engines were run at very modest power levels in relation to their maximum powers. Fuel for the driving engine was provided from a 55-gallon drum in the test cell. Driving engines were provided with a water-out thermocouple to indicate when the engine was warmed up and ready for use.

C. Instrumentation

A Honeywell UDC-500 controller was used to control the temperature in the cold box. The controller received its set point from a Honeywell DCP-7700 set point programmer, which allowed controlled cool-down curves with respect to time. Initial tests with the cold box revealed a tendency to freeze the evaporator coils on humid days. A defrost cycle was added to eliminate the icing. The defrost was set to initiate at midnight and last for 30 minutes. This defrost cycle effectively eliminated the icing problem but introduced a slight perturbation into the cool-down cycle. Since the oil sump has significant thermal mass, the perturbation in the cool-down cycle had minimal impact on the bulk oil temperature.

Each engine was instrumented for oil-sump temperature, oil-suction pressure (in the oil pickup tube), oil-gallery pressure, turbocharger oil pressure (where applicable), engine speed, and in some cases, rocker-arm oiling indication/pressure. The air temperature in the cold box was also measured. Temperatures were measured using type J thermocouples. The oil sump and air temperatures were indicated using a digital readout and recorded during the cool-down period using an ice-point reference and millivolt recorder. The recording of the air and oil temperatures proved to be important since it indicated if any interruptions in the cool-down cycle had occurred. Thus, any runs that were suspect because of evaporator icing, power failure, a door left ajar, etc., were eliminated. Oil pressures were measured using Sensotec amplified pressure transducers placed as close to the measured fluid as possible. In the case of gallery and turbo pressures, the transducers were screwed directly to the block or supply hose. In the case of the oil suction pressure, a 0.25-inch copper line was brazed to the pickup tube and run to the exterior of the engine in order to attach the pressure transducer. Each of the pressure transducers was recorded on a stripchart recorder during the pumping part of the experiment.

Engine speed was measured using a 60-tooth gear and a magnetic pickup. The output of the magnetic pickup was routed to a digital frequency meter in order to monitor engine speed. The frequency was also routed to a frequency-to-voltage converter and thence to the chart recorder. This pathway provided immediate feedback to the operator controlling motoring speed and a record of speed.

Rocker arm oiling was measured in one of two ways. In the case of the Cummins VTA-903T and DDC 6V-53T engines, a 15-psig pressure transducer was plumbed directly to the rocker shaft. This was possible since both engines use a pressurized rocker shaft. In the case of the GM 6.2L engine, however, a pressurized push rod lubricates the rocker arm by drip feed. In order to obtain an indication of rocker arm oiling, a vacuum system was used to indicate the presence of oil in the rocker arm. A small electrically powered vacuum pump was used to provide vacuum to the system. The vacuum was piped to a T-connection with needle valves on both arms. One needle valve opened to atmosphere and the other opened to another T-connection. This T-connection had a vacuum gauge (0 to

15 inches of water) on one leg and a tube to the engine on the other. The tube to the engine was large (0.25 inch) until just before the rocker arm. At the rocker arm, a 1/16-inch stainless steel tube was connected and immersed in the pool of oil in the rocker arm. In practice, the rocker arm was drained of oil and washed with solvent before the test. The vacuum pump was turned on and the valves adjusted to provide a mid-scale reading on the vacuum gauge. With the rocker arm drained and clean, only air was sucked through the 1/16-in tube. When rocker-arm oiling occurred, oil was sucked into the small tube and the indicated vacuum increased. This method proved to be very dependable in indicating rocker-arm oiling. A visual method was used to confirm the rocker-arm oiling apparatus. A change in capacitance method was also tried, but the dielectric difference between oil and air was insufficient to provide reliable indications of rocker-arm oiling.

E. Other Details

The normal engine-mounted water pump was used to circulate a 50/50 volumetric blend of commercial antifreeze and water in the cooling passages of the engine. A 1000-watt immersion heater was plumbed in the cooling line to facilitate warmup of the engine for purposes of oil flush. Circulation ran from the engine to the water pump to the heater and back to the engine.

The fuel system of the first engine tested (the Continental LDT-465-1C) was plumbed to circulate fuel from a small container to the injector pump with return fuel being routed back to the container. This cycle caused problems in that dribble from the injectors (even in the no-rack position) caused exhaust fumes to fill the refrigerated box. This was initially cured by removing the pistons, connecting rods, and fuel injectors and routing fuel only to the injector pump (for lubrication). This approach was desirable since a motoring dynamometer was used for a short time to motor the engine. The removal of the pistons and connecting rods lowered the motoring friction and made the use of the motoring dynamometer possible. Later in the program, this approach was deemed unrealistic since the connecting-rod lubrication system was eliminated with this approach. The alternate approach was to reinstall the pistons and connecting rods, let the fuel lines to the injectors drain into the fuel supply can, and switch to the engine-powered motoring system already described. Each of the fuel systems in the test engines was disabled to prevent exhaust fumes from being present in the box. The Cummins

903T fuel system was disabled by removing the fuel injector pushrod and removing the fuel injection pump. The GM 6.2L fuel system was disabled by utilizing the built-in fuel shutoff solenoid. The DDC 6V-53T fuel system was disabled by wiring the rack control in the no-fuel position.

Four 250-watt infrared heating lamps were placed under the oil sumps of the engines. These lamps provided rapid heatup of the oil sump without disturbing the internal oil-pan geometry with heating coils. A 1000-watt heating element was placed in the cooling water circulation path to facilitate engine warm-up.

Each test lubricant was stored in an electrically heated drum for at least 24 hours prior to testing and for the duration of testing. The temperature of the lubricant was maintained at 180°F (82°C) in order to provide all test lubricants with uniform temperature histories and destroy any previous temperature history.

APPENDIX B

Test Procedure

The following test procedure was used for the lubricant pumpability determinations:

After a pumping attempt,

1. Raise oil temperature to 110°F (43°C) by turning on heating lights, turning on water heater (meters should read 1000 watts), and motoring at 800 rpm. This was done in order to facilitate drainage.

2. Turn off lights and heater.

3. Drain oil and save in used oil drum.

4. Remove filters and reinstall housings. This was done to minimize used oil hangup in the engine.

5. Fill with hot test oil (180°F). This is a flush using the next test lubricant.

6. Motor at 800 rpm for 10 minutes. This is a flush run.

7. Drain oil and dispose. This lubricant is a mix of old and new lubricant and is therefore disposed.

8. Fill with hot test oil (180°F). This is new test lubricant.

9. Motor at 800 rpm for 10 minutes. This is another flush run.

10 Drain oil and save in used oil drum.

11. Install filters. This is in preparation for the test run.

10:30 am

12. Fill with measured amount of hot test oil (180°F).

13. Motor at 800 rpm for 1 minute.

14. Program set point programmer for desired cooling curve.

11:40 am

15. Start cooling, recording temperatures at a chart speed of 2 cm/hr. Check to make sure air and oil-sump temperatures are recording properly.

8:00 am (next day)

16. Install all pens in chart recorder. Turn on speed recorder. Shift transmission into neutral and warm cranking engine to 170°F (77°C) water-out temperature. Disengage clutch and shift into reverse. Remove box and sump indicating pens to avoid interference w/others. Turn on remaining pens on recorder and set speed to 2 cm/min. Check to make sure all pens are functioning correctly. Engage clutch and blip oil gallery pen simultaneously.

17. Motor engine at test speed for 15 minutes.

18. Turn off chart recorder and cap all pens.

19. Turn off cooling.

20. Turn on heating lights.

21. Turn on water heater and motor at 800 rpm until oil temperature reaches 110°F (43°C). Oil temperature will rise approximately 2°F (-17°C) per minute. Check speed occasionally and maintain 800 rpm.

22. Stop engine, turn off lights and heaters, open box.

23. Drain oil and oil filters. Four-ounce sample of used oil to chemical laboratory. Label sample with AL No., cranking temperature, and date. Save drained oil in used oil drum.

24. Sponge up any fluid that has condensed or spilled on floor.

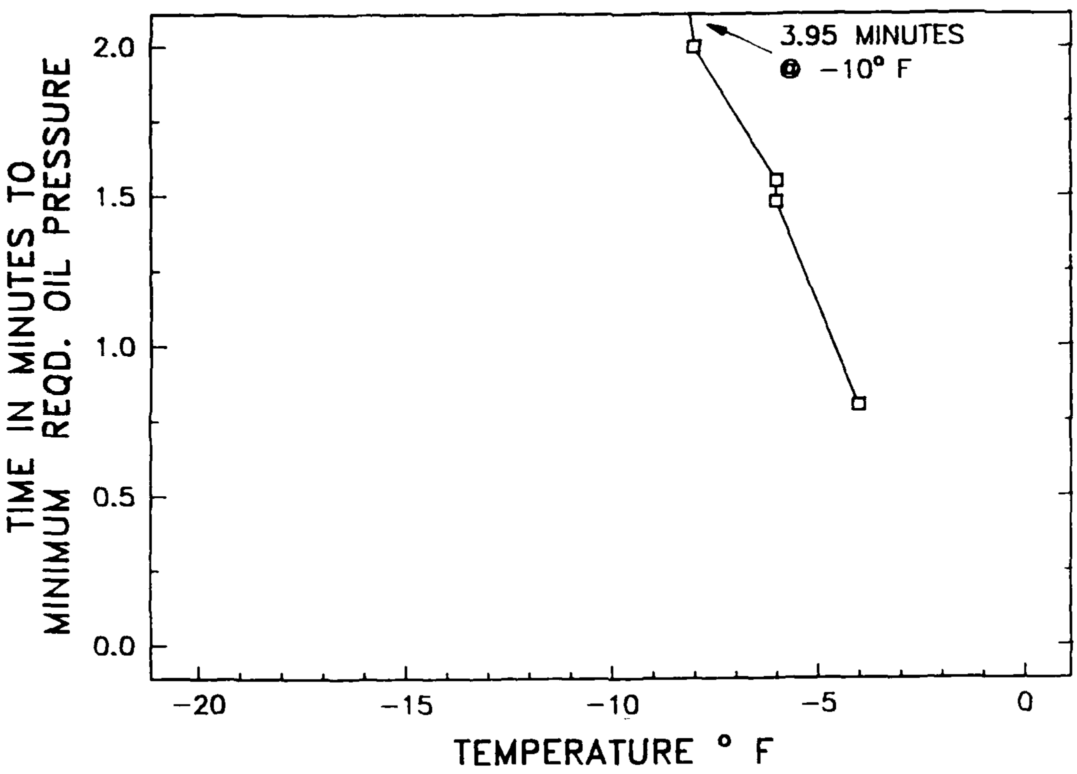
25. If the next lubricant is the same as the last lubricant, go to step 12. If the next lubricant is a different lubricant, go to step 4.

Quantities of lubricant used in each engine were 38.2 lb (17.3 kg) for the LDT-465-1C engine, 38.2 lb (17.3 kg) for the Cummins VTA-903T, 11.6 lb (5.3 kg) for the GM 6.2L engine, and 43.0 lb (19.5 kg) for the DDC 6V-53T engine. The time table shown in the procedure was intended to provide each run with the same amount of cold-soak time, while still allowing adequate time to change lubricant and prepare for the next day's run. In some instances, the cold soak was extended over a weekend to investigate the effect of longer cold-soak periods. Normal cold-soak time was 20 hours total, or 68 hours over the weekend.

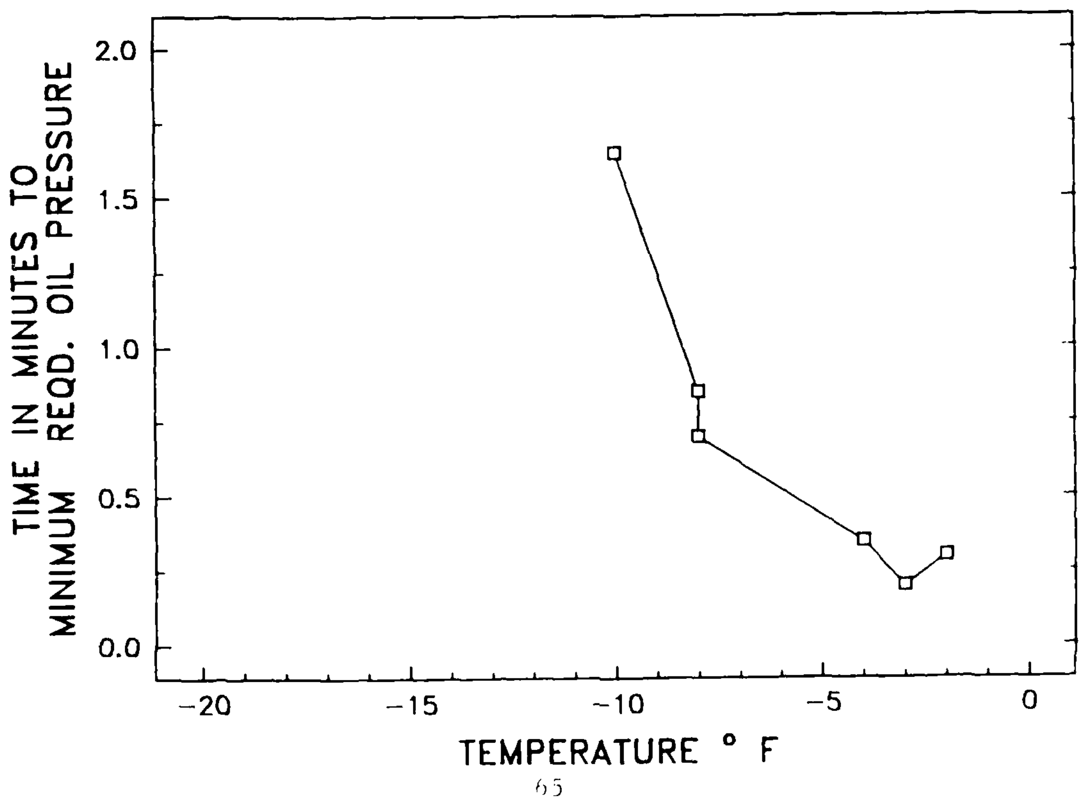
APPENDIX C

Low-Temperature Oil Pumpability
in the LDT-465-1C Engine

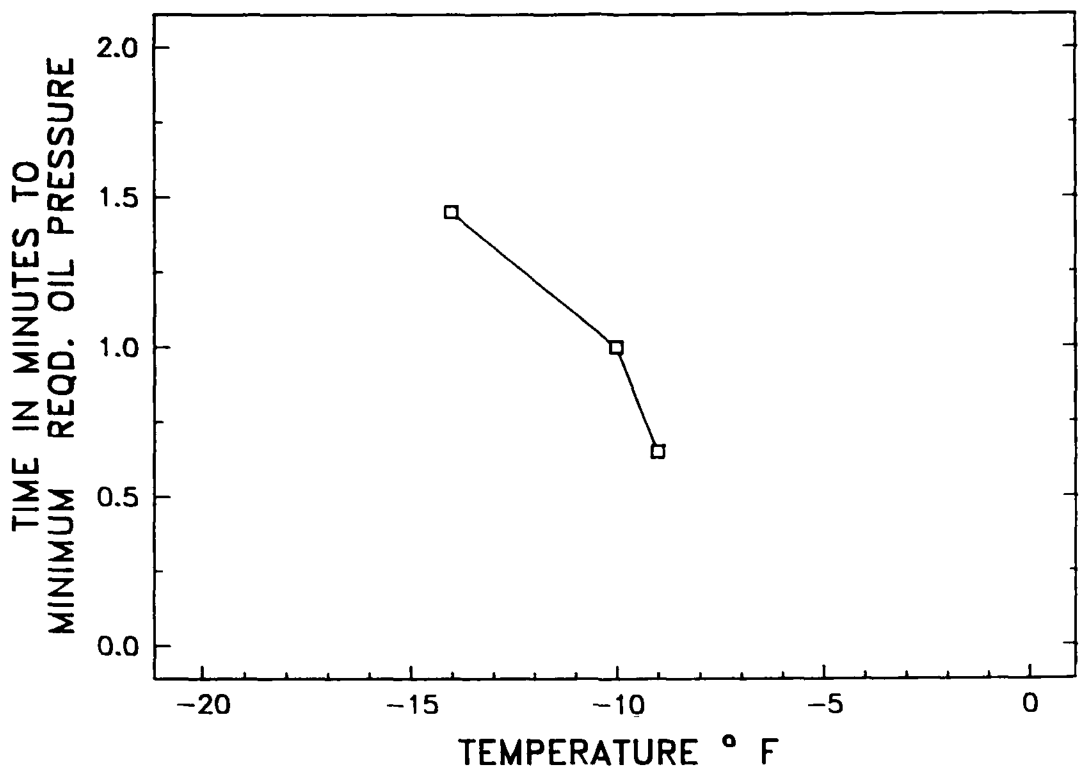
LDT-465 15W40 OIL NO. 1 (OCP) 82CP



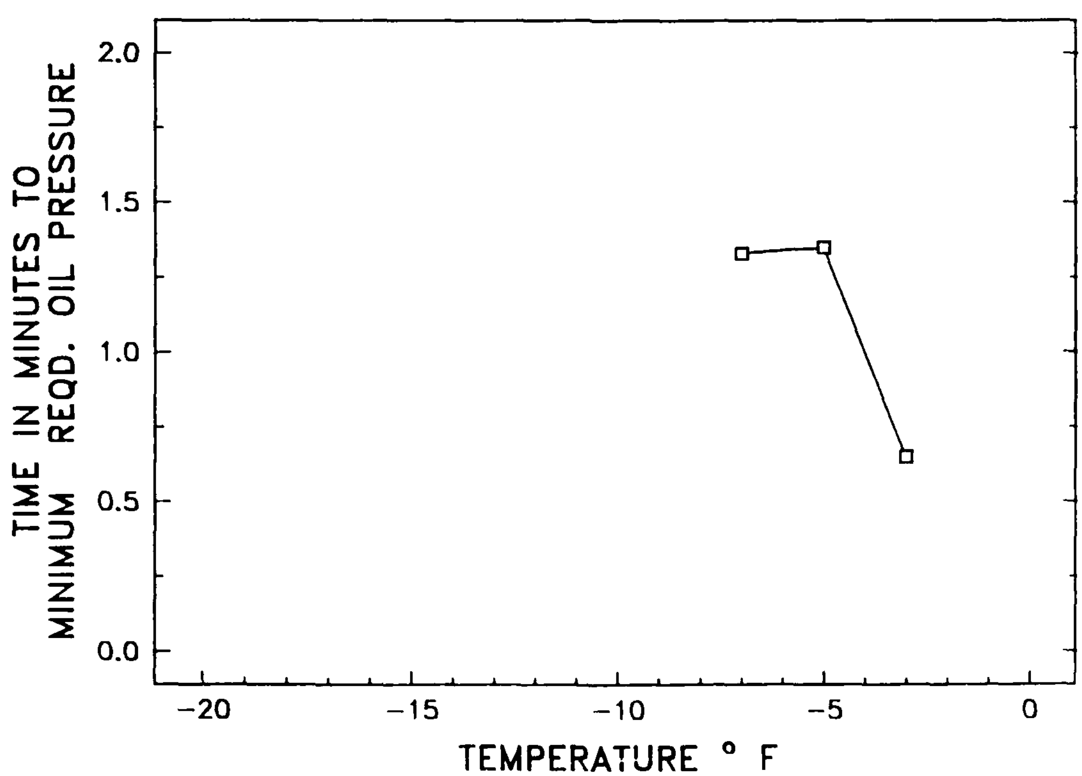
LDT-465 15W40 OIL NO. 2 (OCP) 82CP

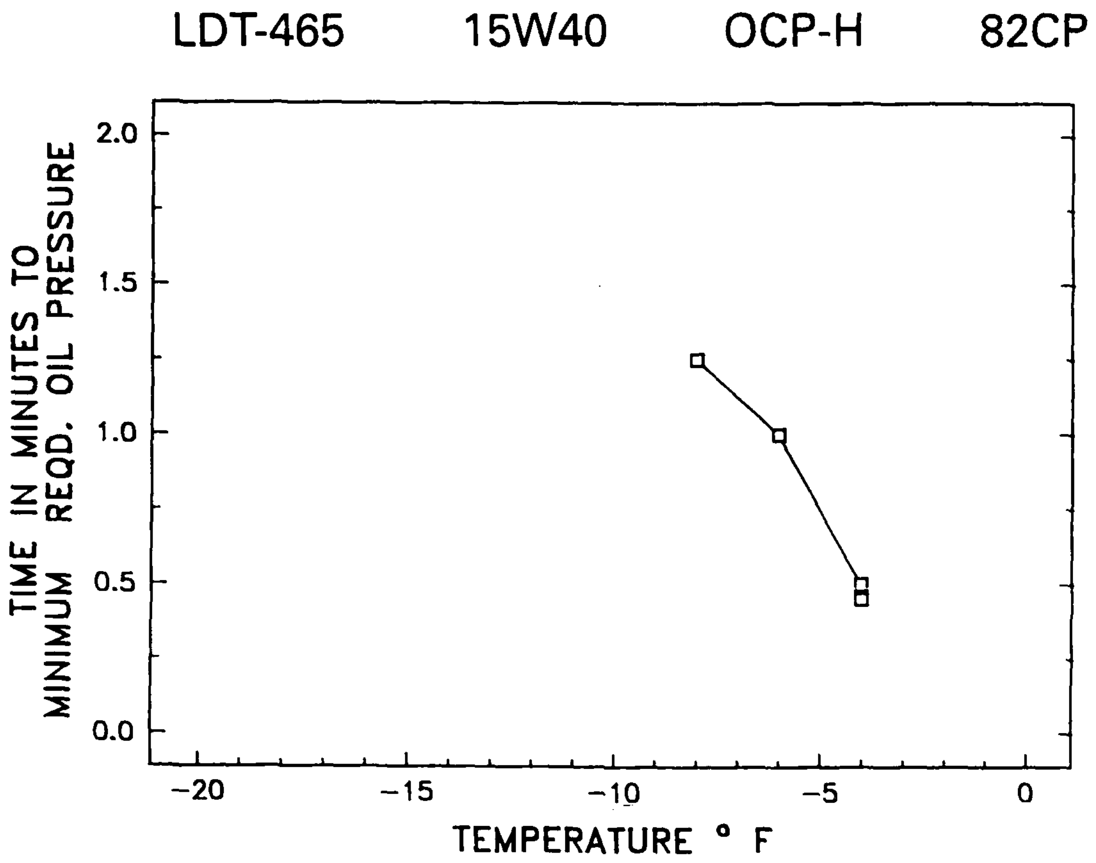


LDT-465 15W40 OCP-L 82CP

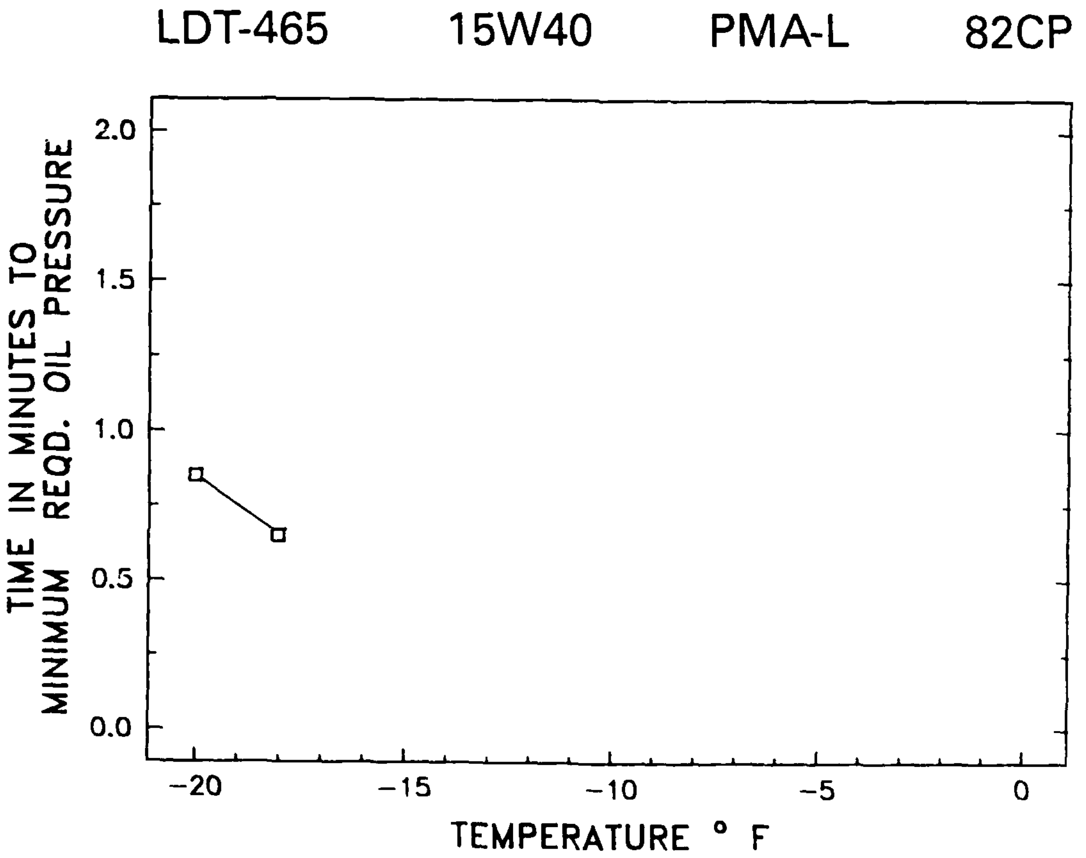


LDT-465 15W40 OCP-H



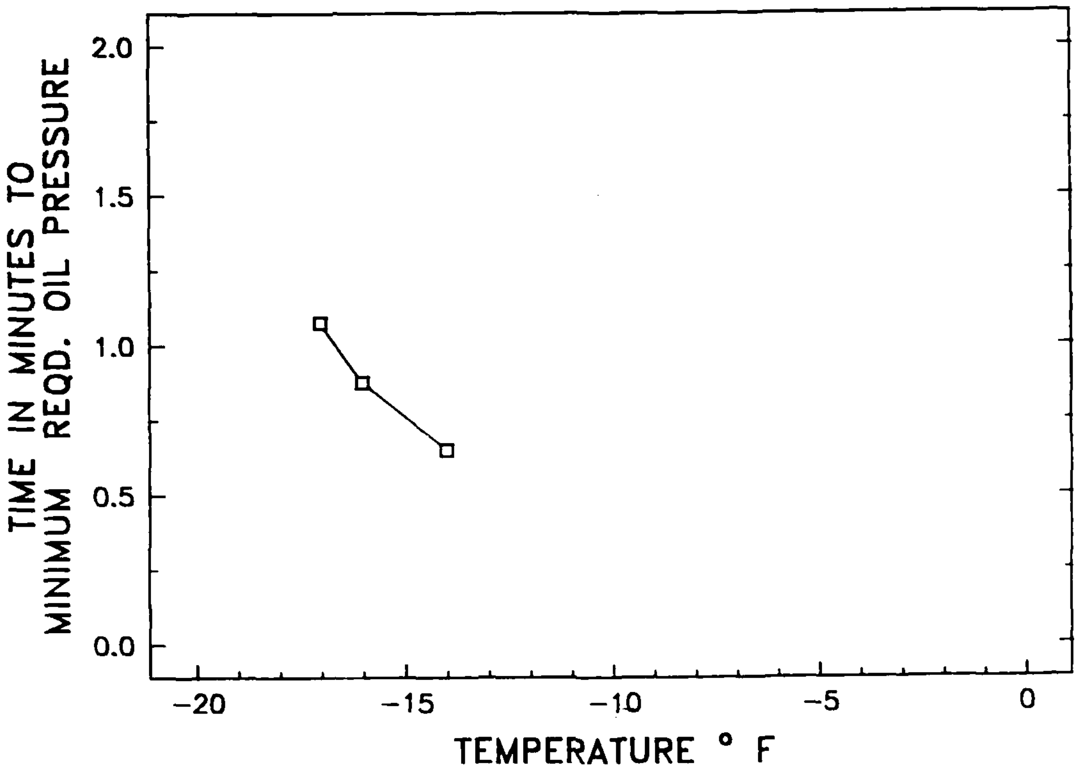


LDT-465 15W40 OCP-H 82CP
TIME IN MINUTES TO MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F

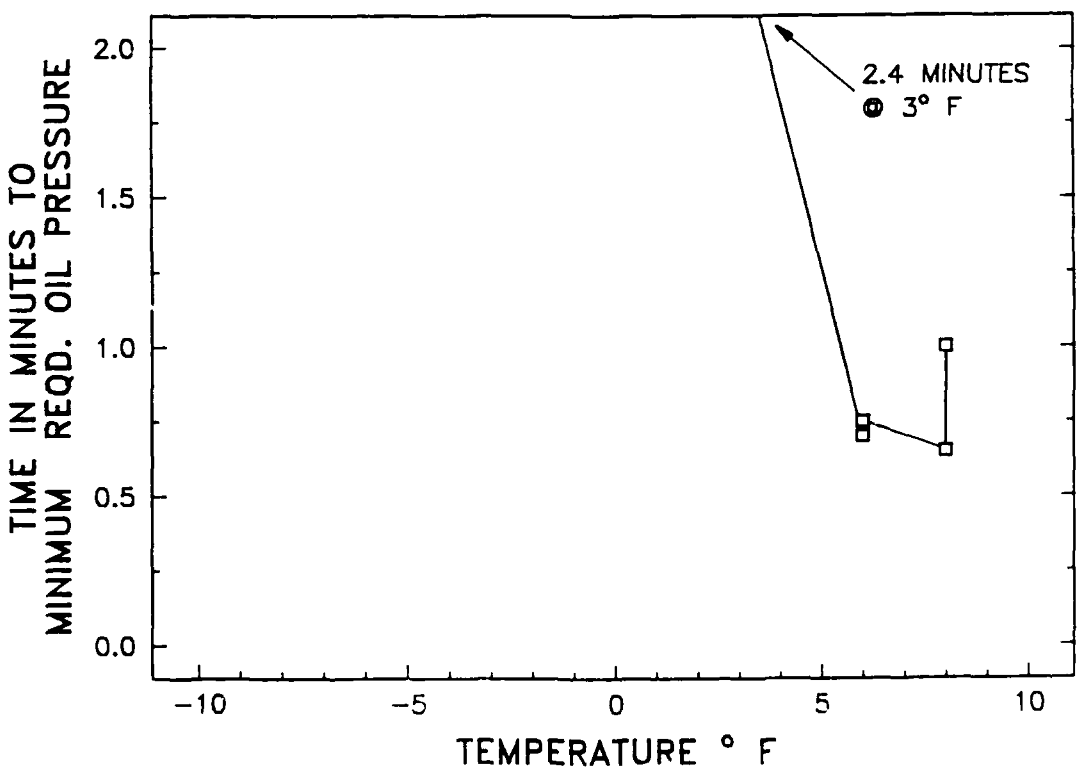


LDT-465 15W40 PMA-L 82CP
TIME IN MINUTES TO MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F

LDT-465 15W40 PMA-H 82CP



LDT-465 30 GRADE OIL NO. 11 75VI



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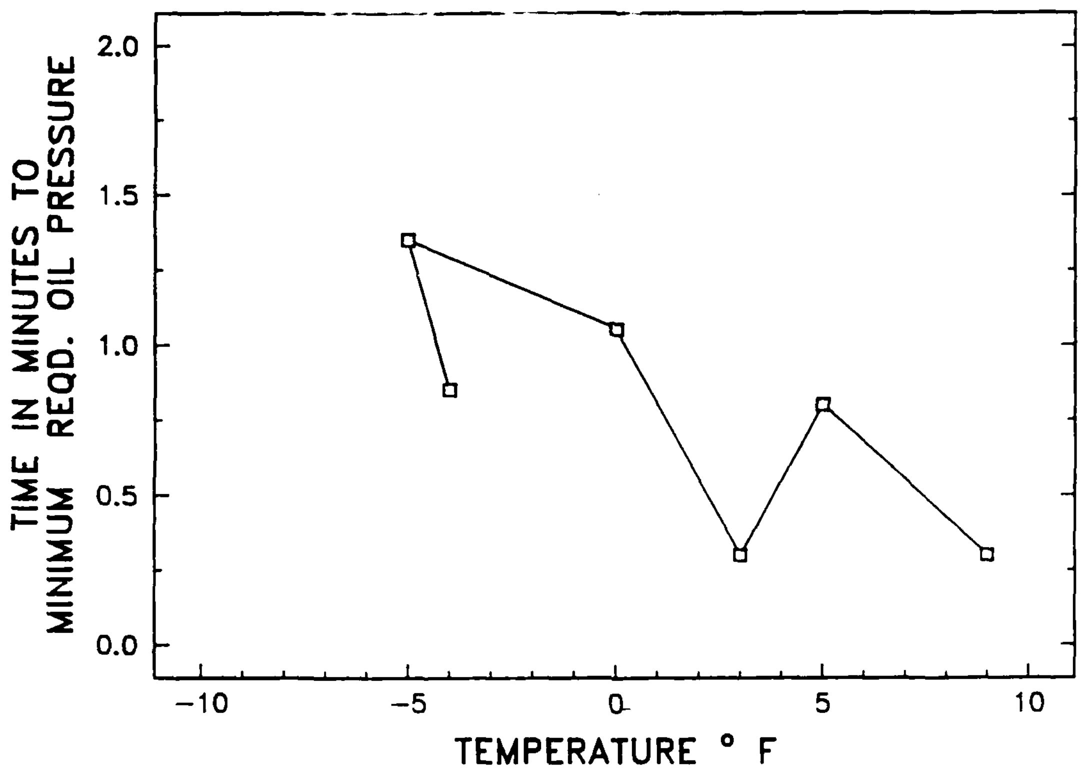
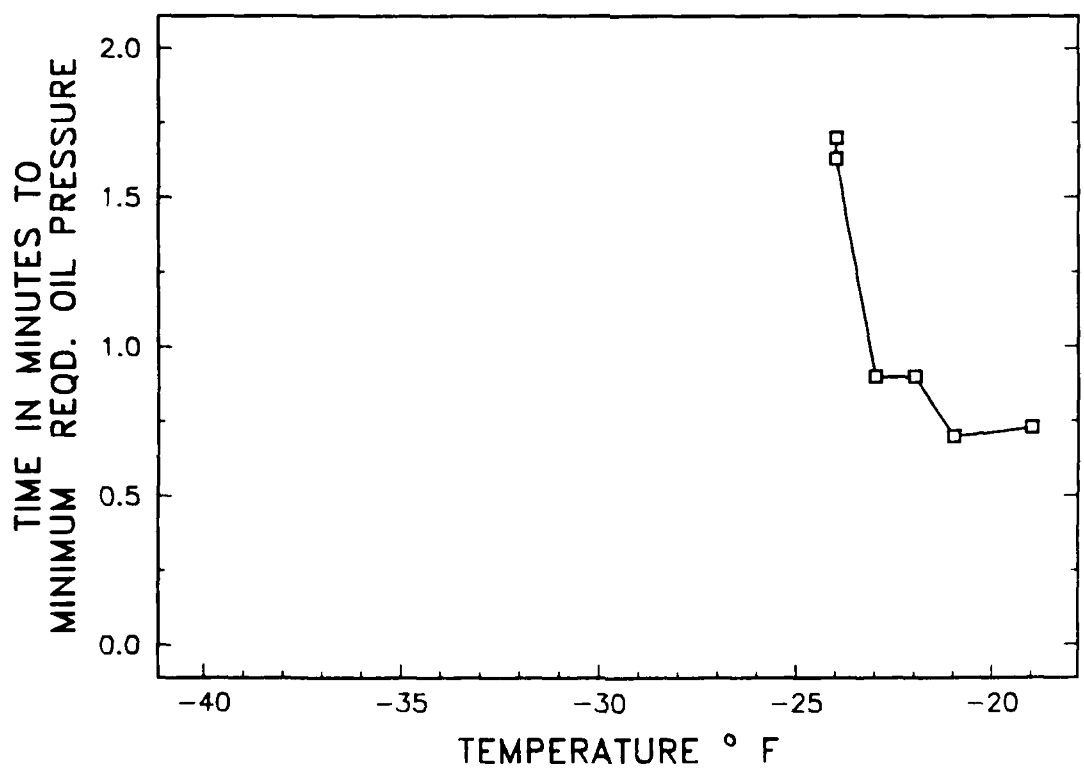


LDT-465 10W OIL NO. 13



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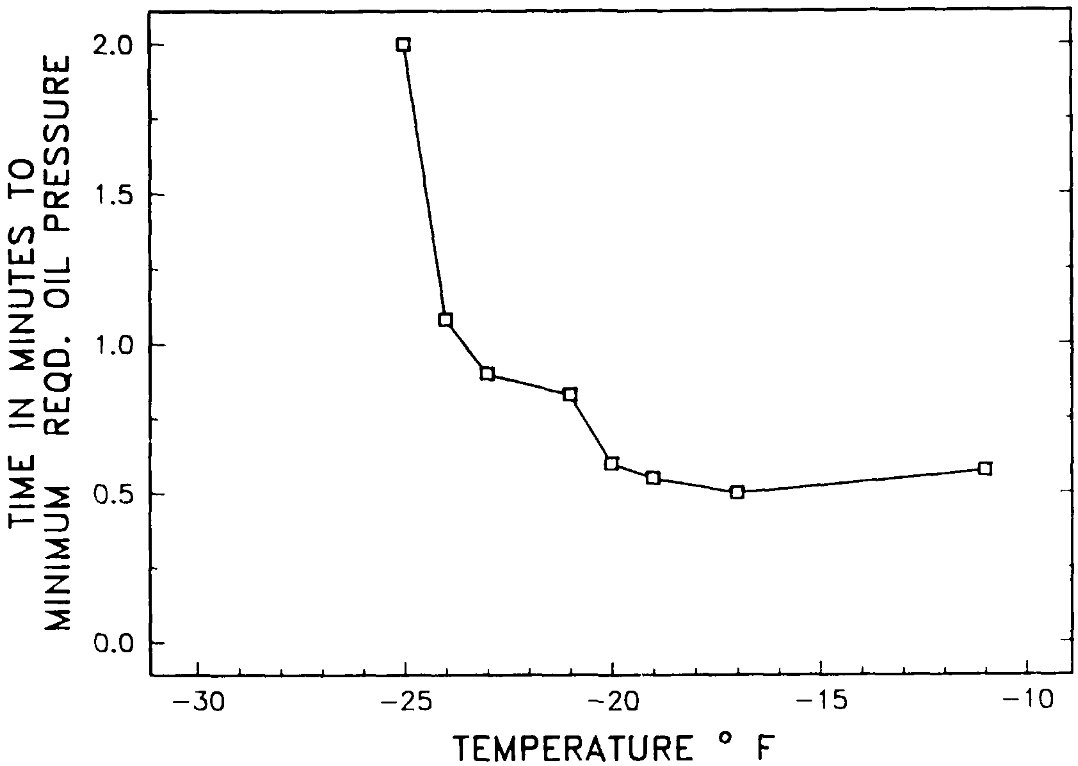
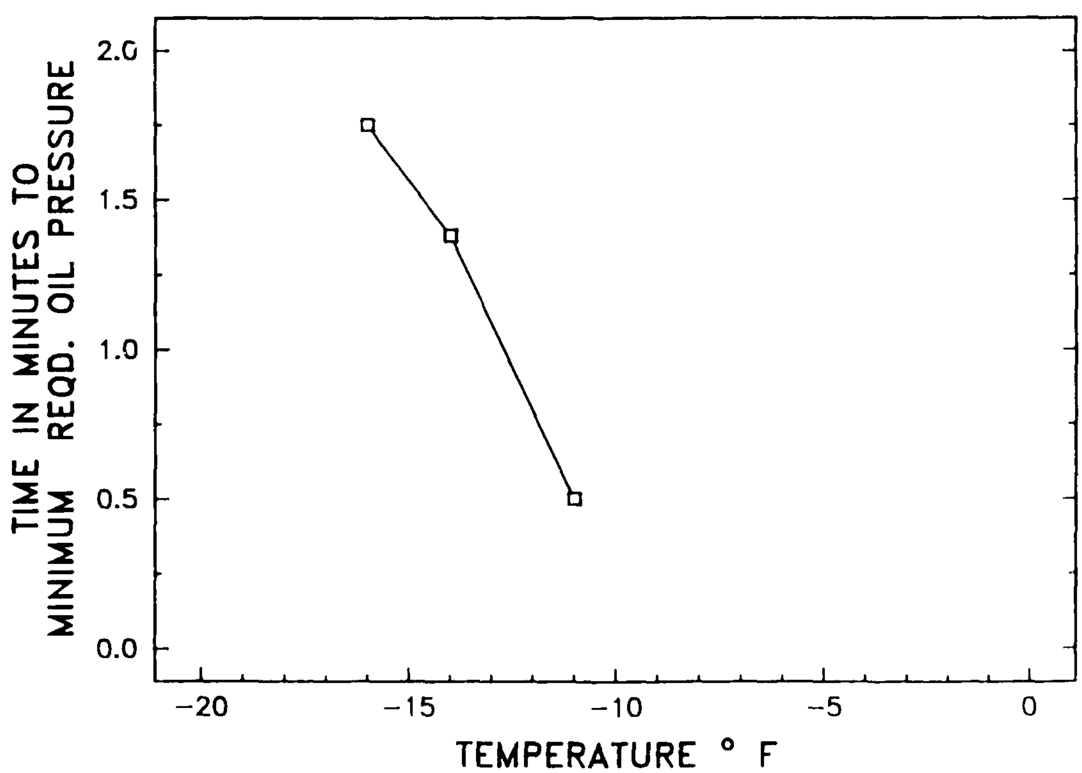
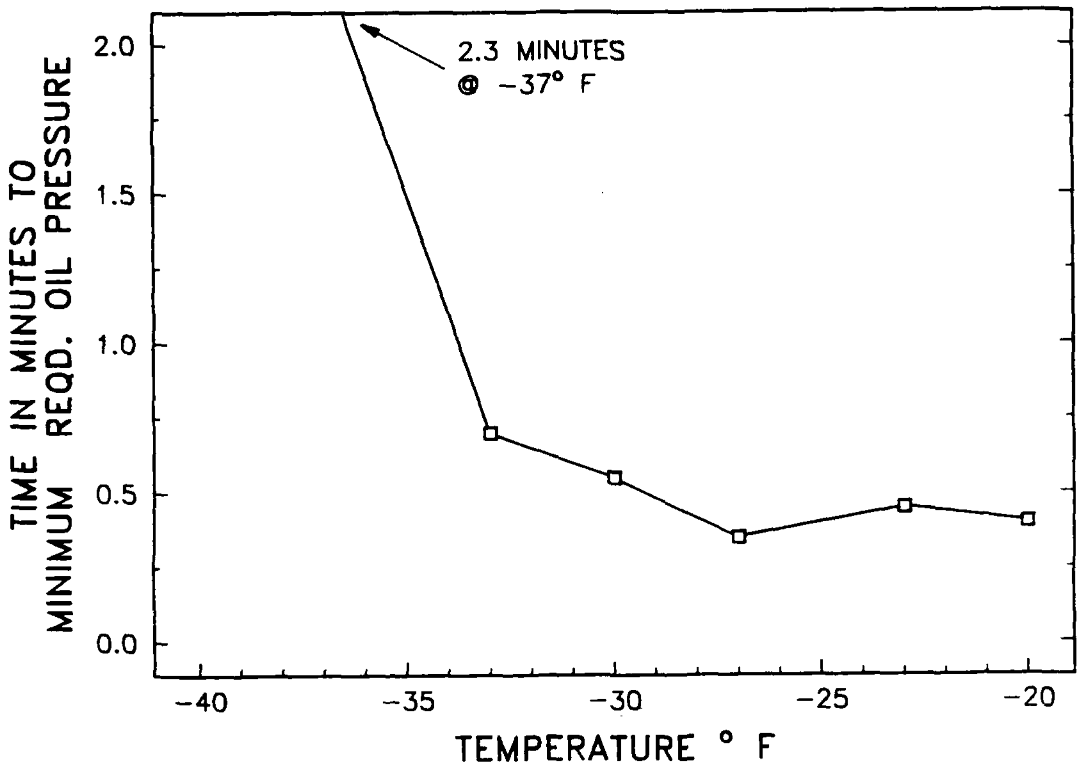


LDT-465 10W30 OCP-L 82CP

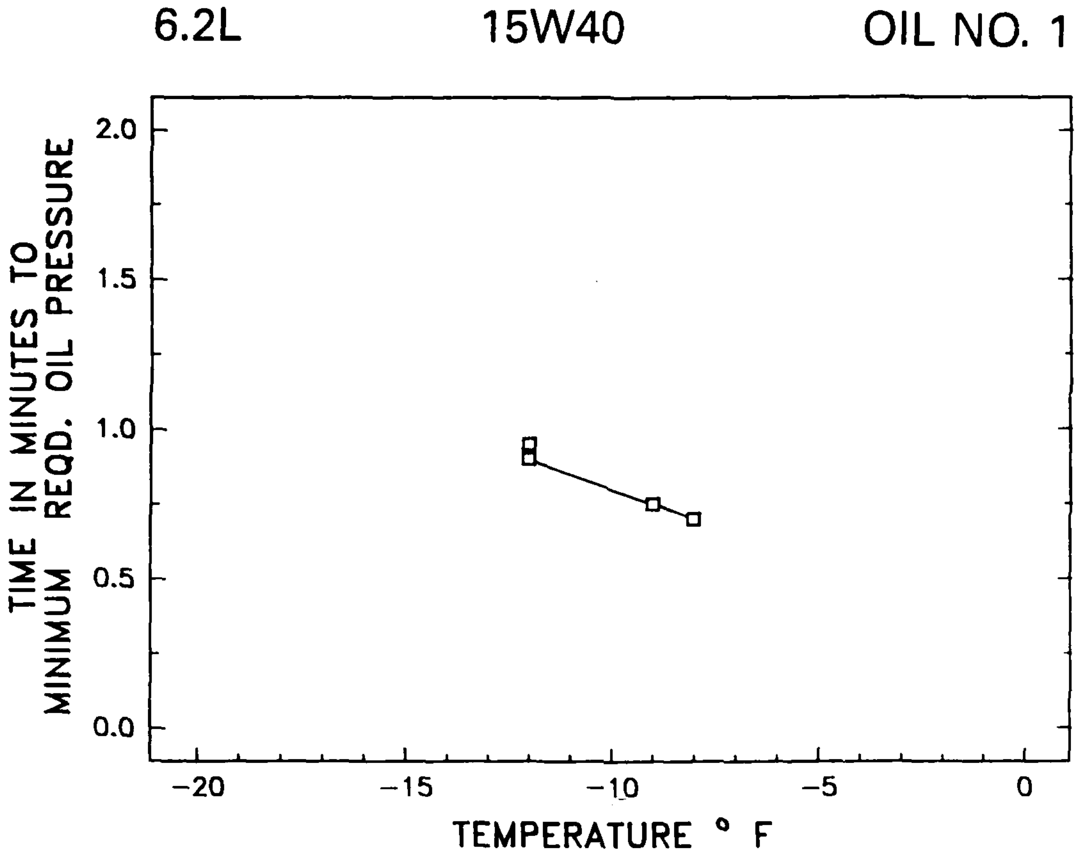


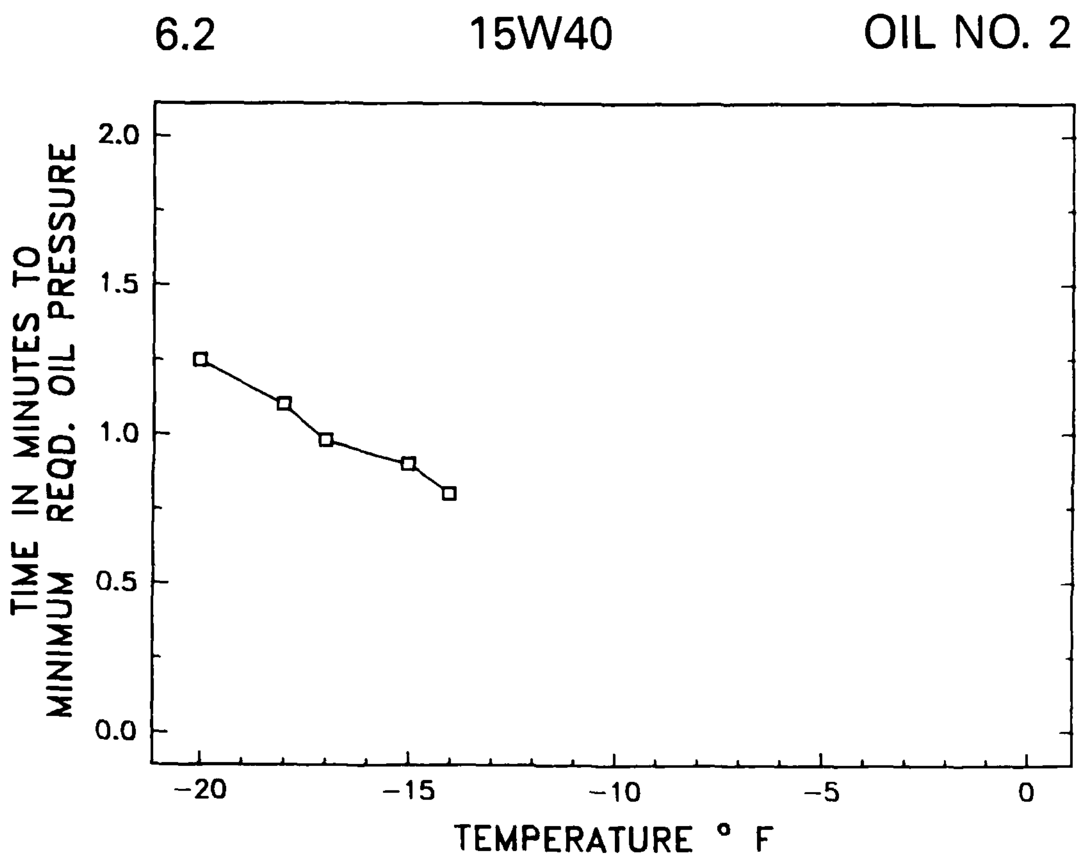
LDT-465 5W30 OIL NO. 16



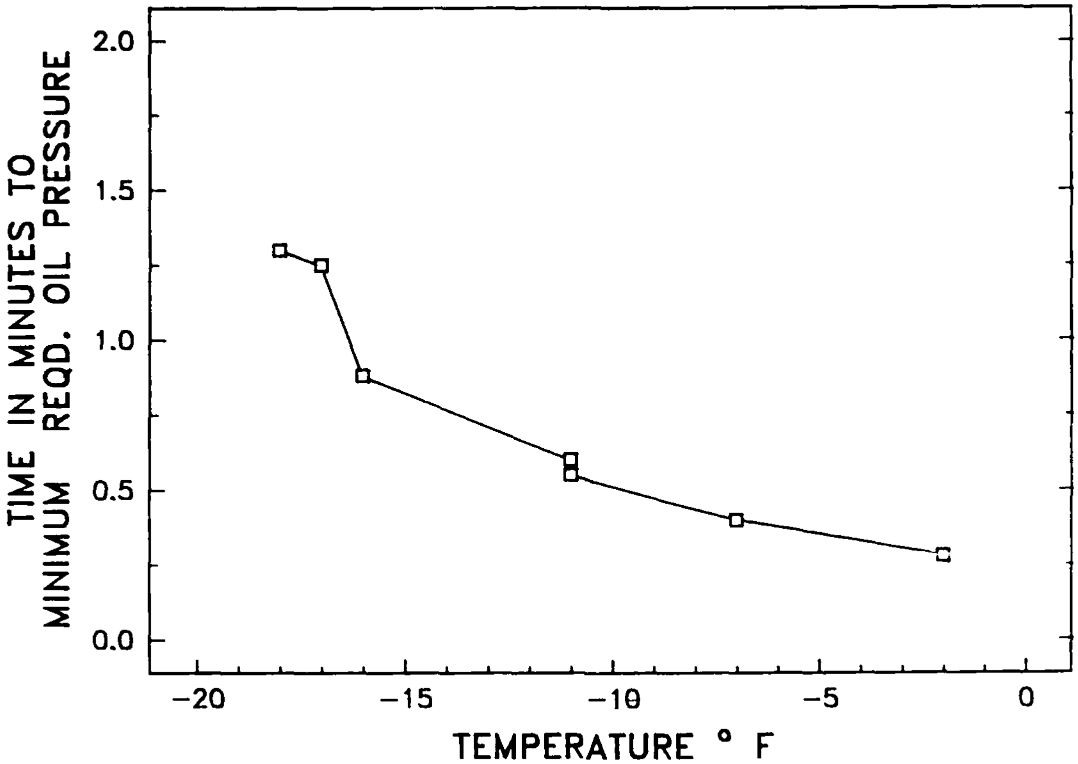
APPENDIX D

Low-Temperature Oil Pumpability
in the GM 6.2L Engine

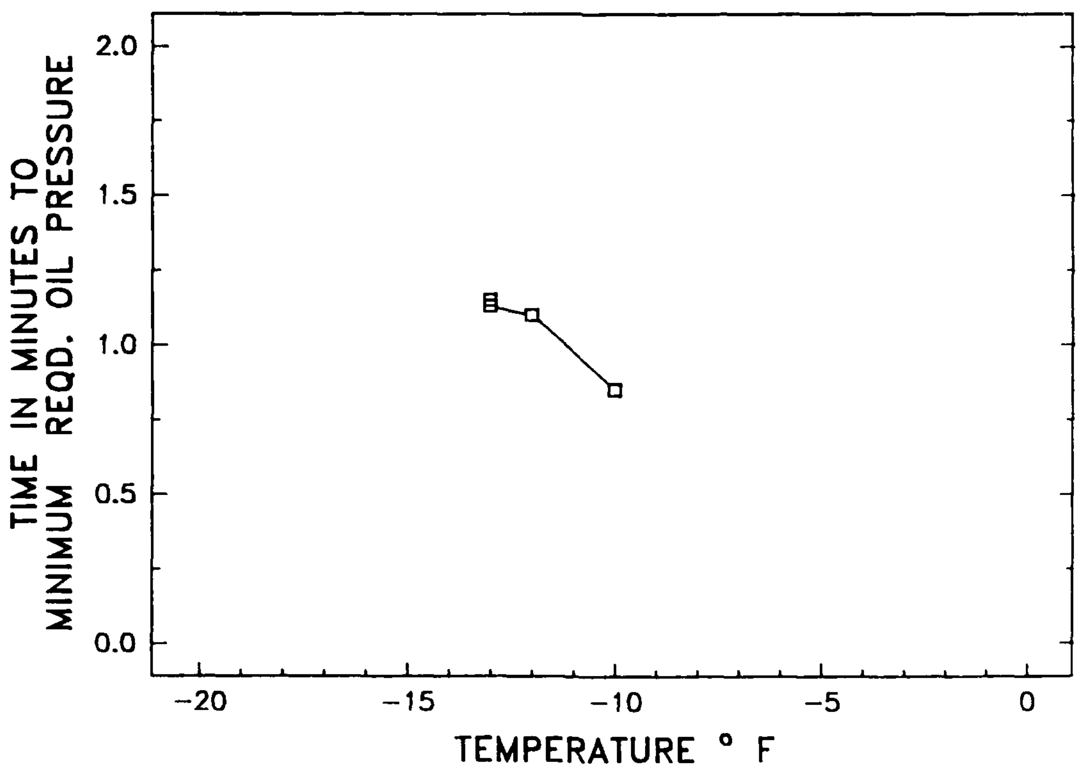

6.2L
15W40
OIL NO. 1
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F


6.2
15W40
OIL NO. 2
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F

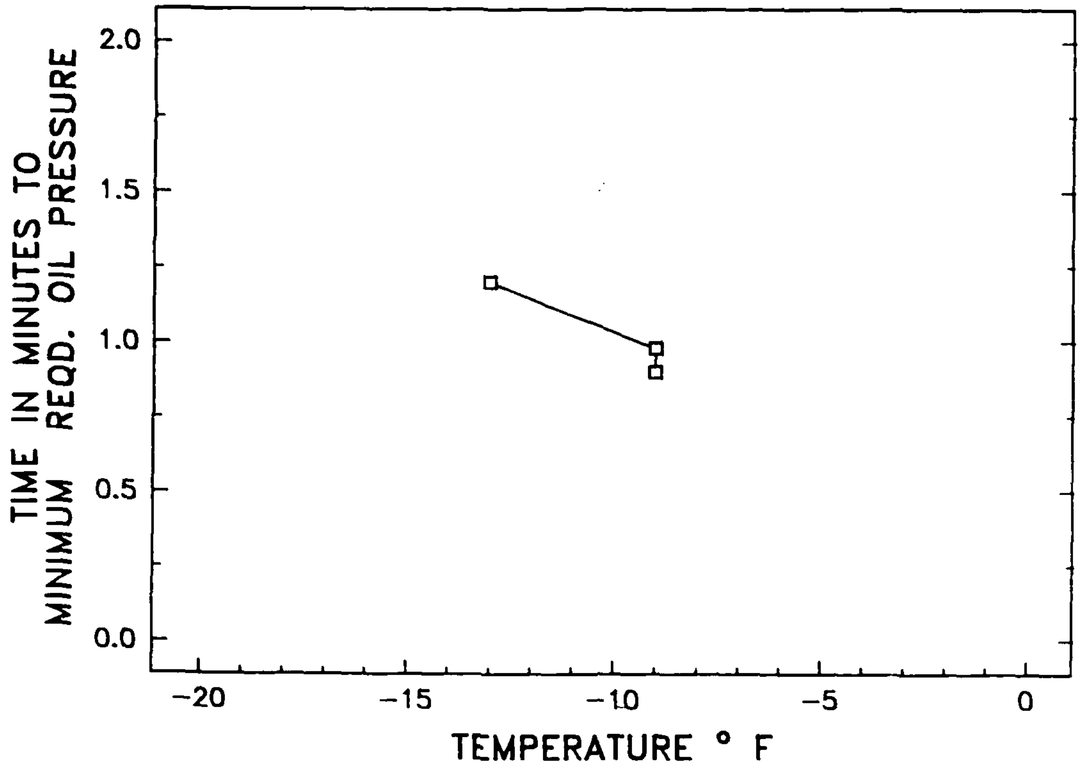
6.2L 15W40 OCP-L



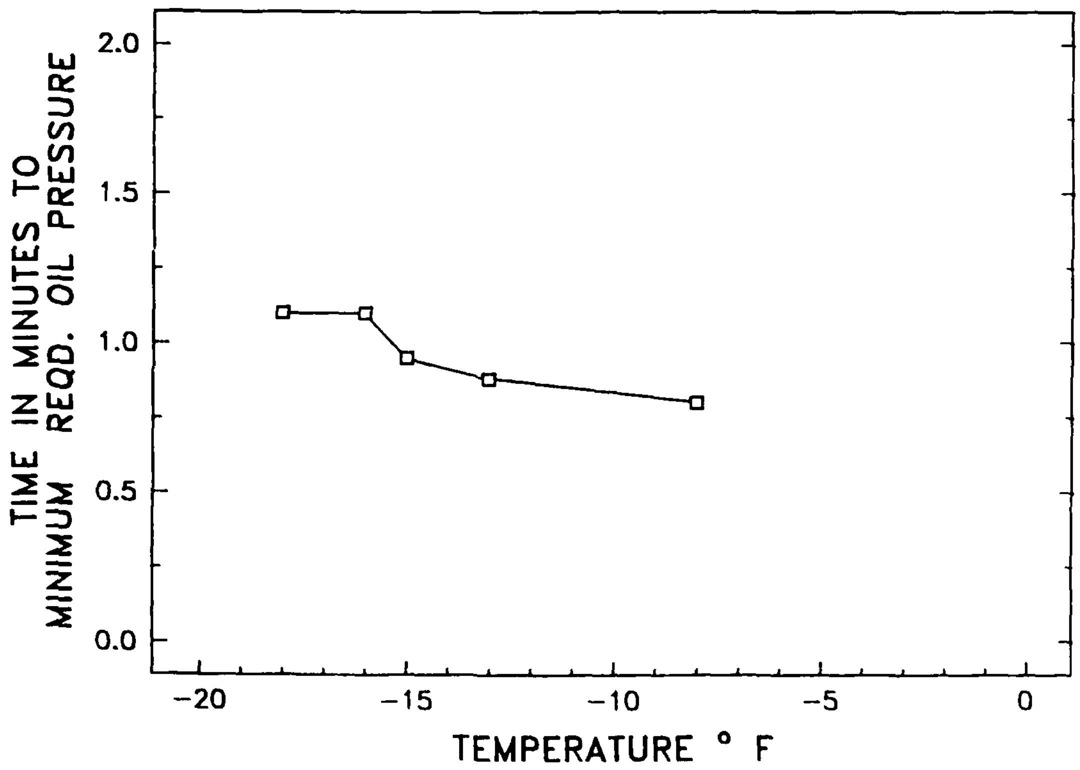
6.2L 15W40 OCP-H

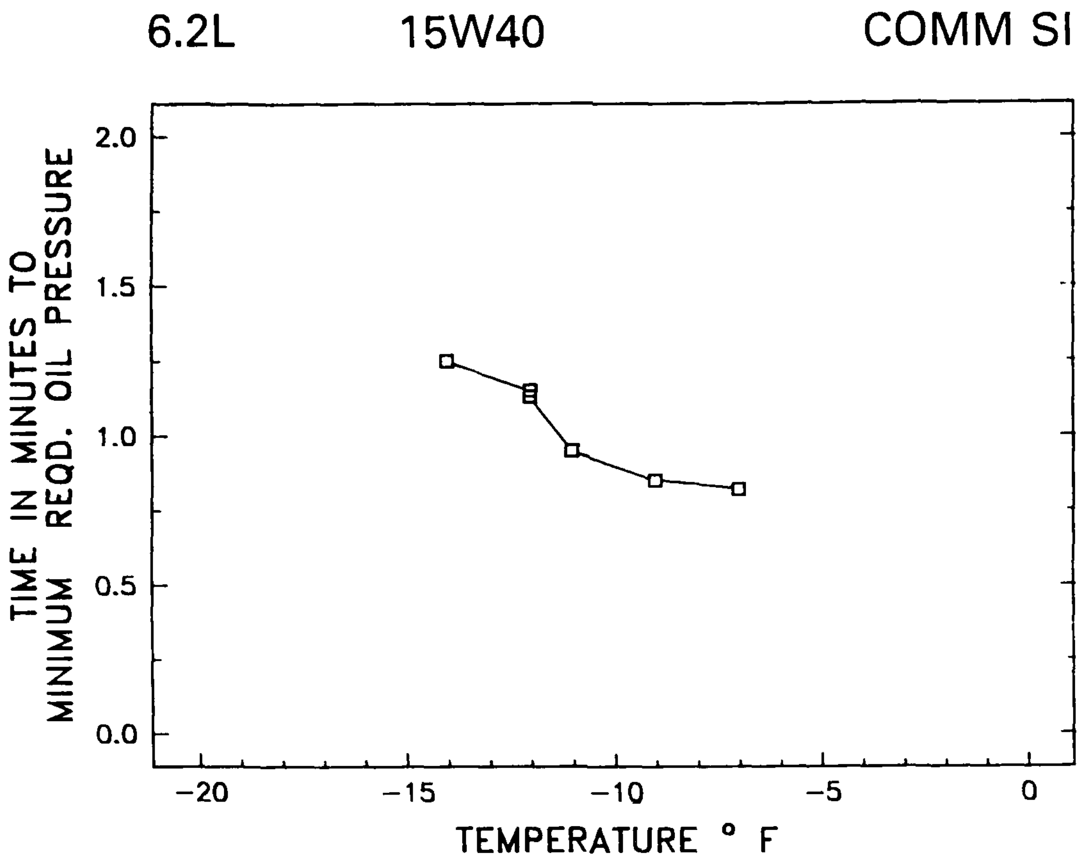


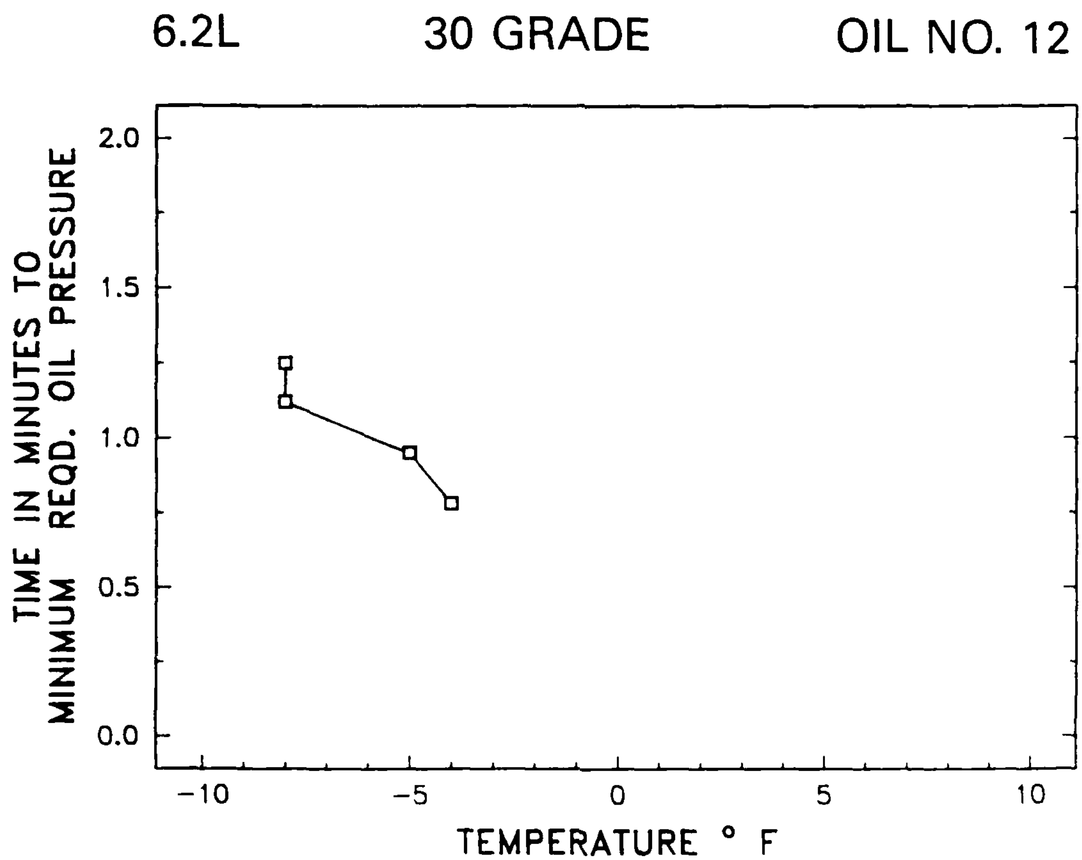
6.2L 15W40 SI-H



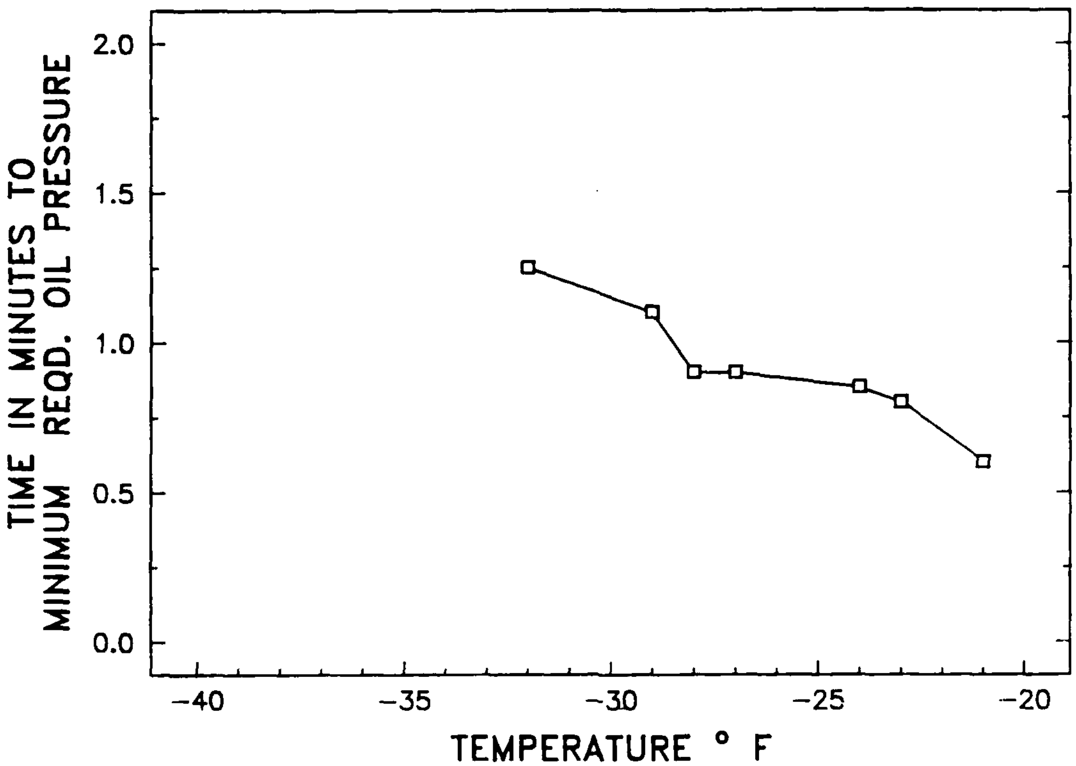
6.2L 15W40 SI-L



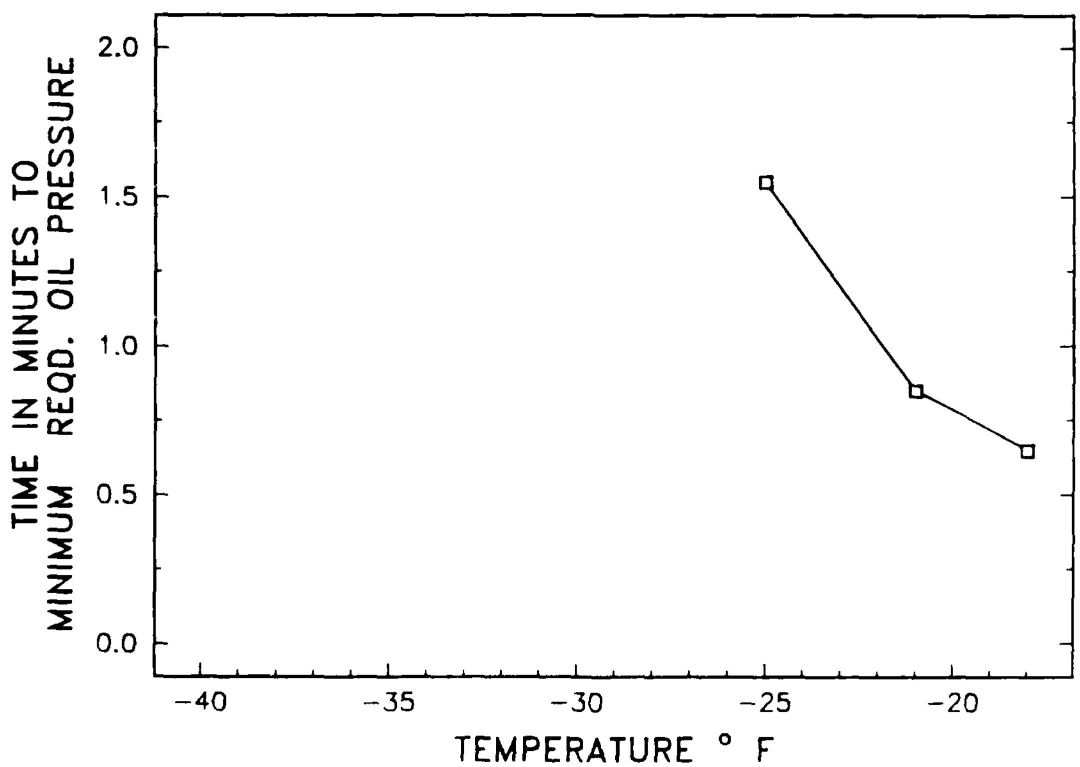

6.2L
15W40
COMM SI
TIME IN MINUTES TO MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F


6.2L
30 GRADE
OIL NO. 12
TIME IN MINUTES TO MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−10
−5
0
5
10
TEMPERATURE ° F

6.2L 10W OIL NO. 13



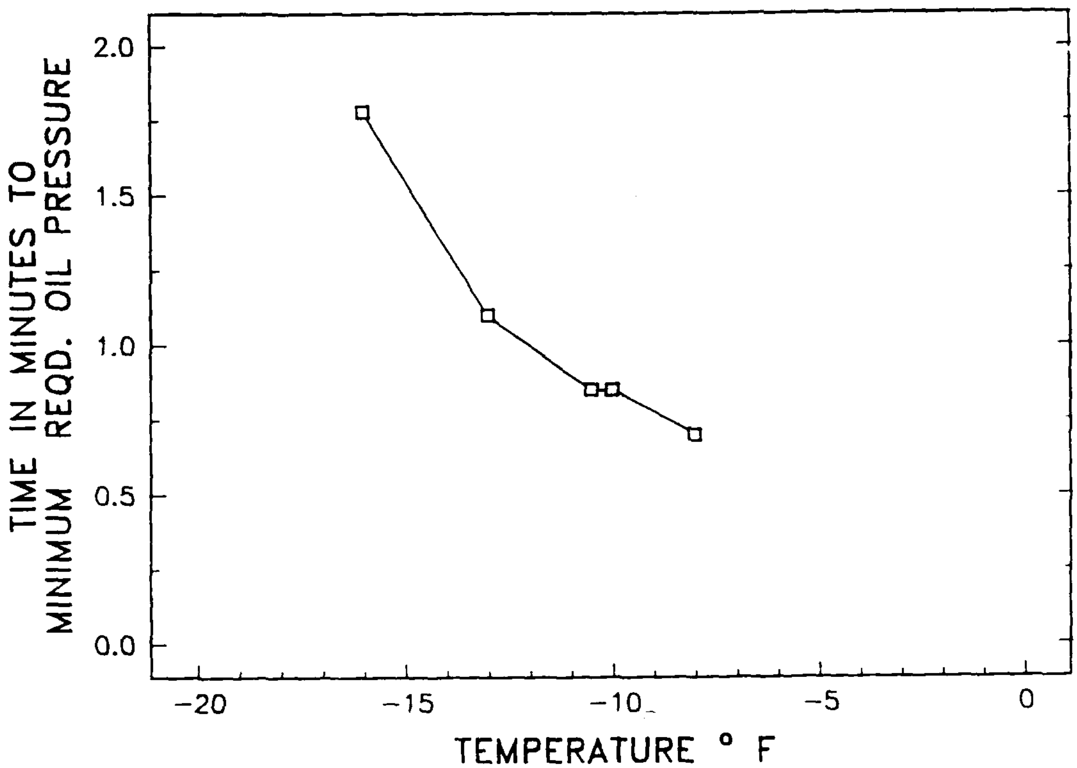
6.2L 10W30 OCP-L



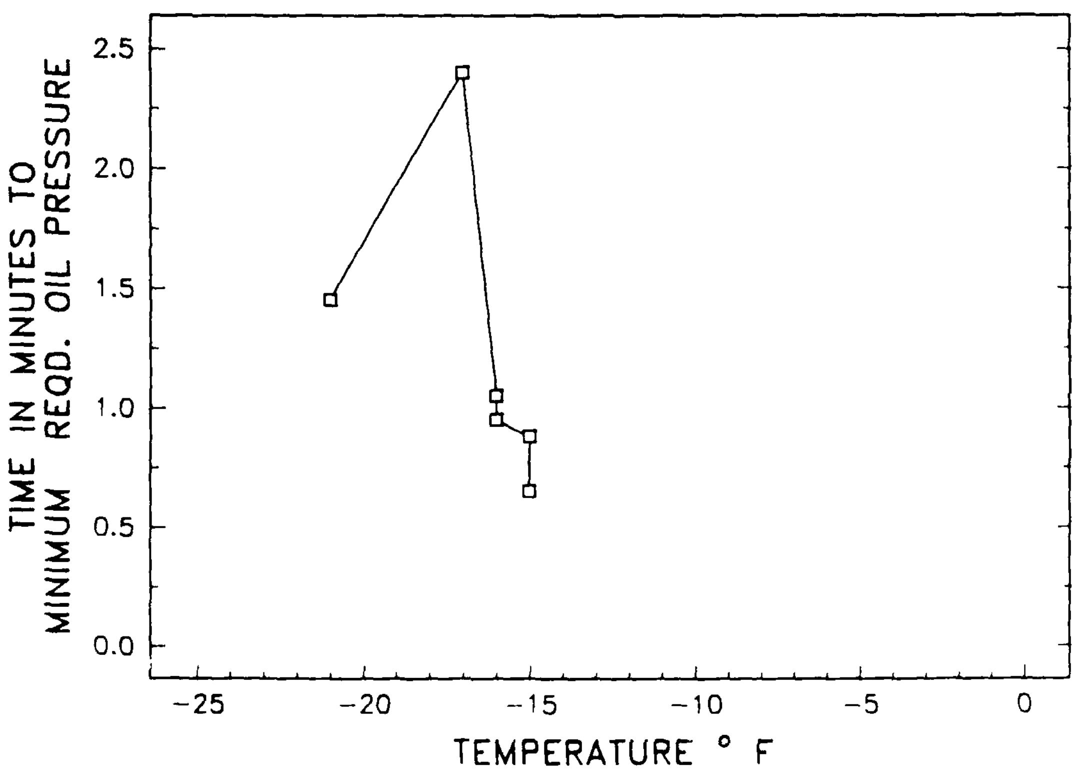
APPENDIX E

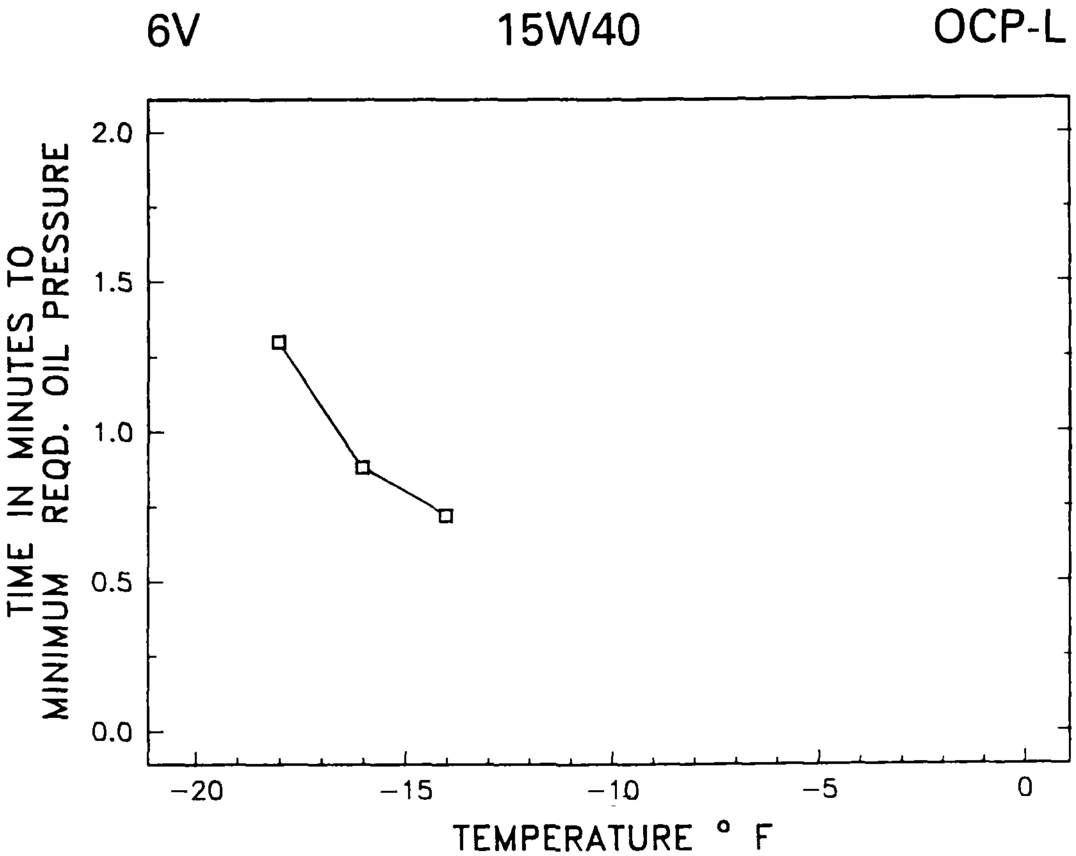
Low-Temperature Oil Pumpability in the DDC 6V-53T Engine

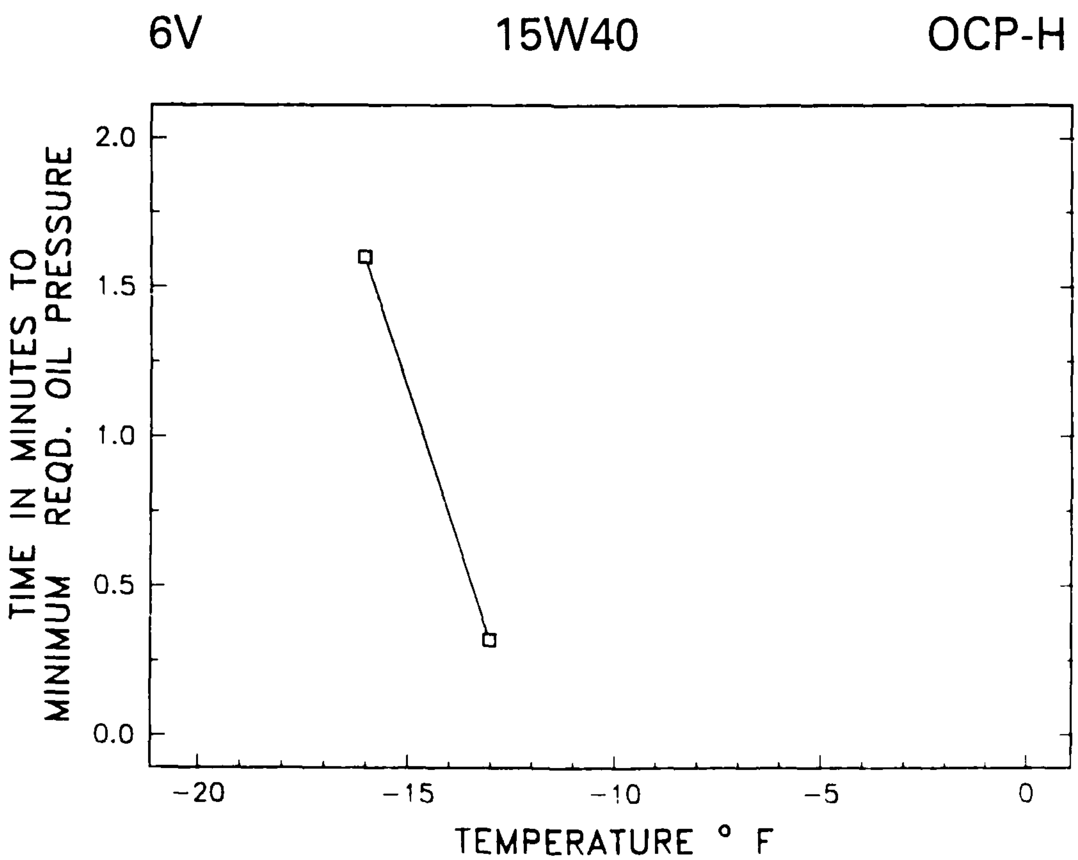
6V 15W40 OIL NO. 1

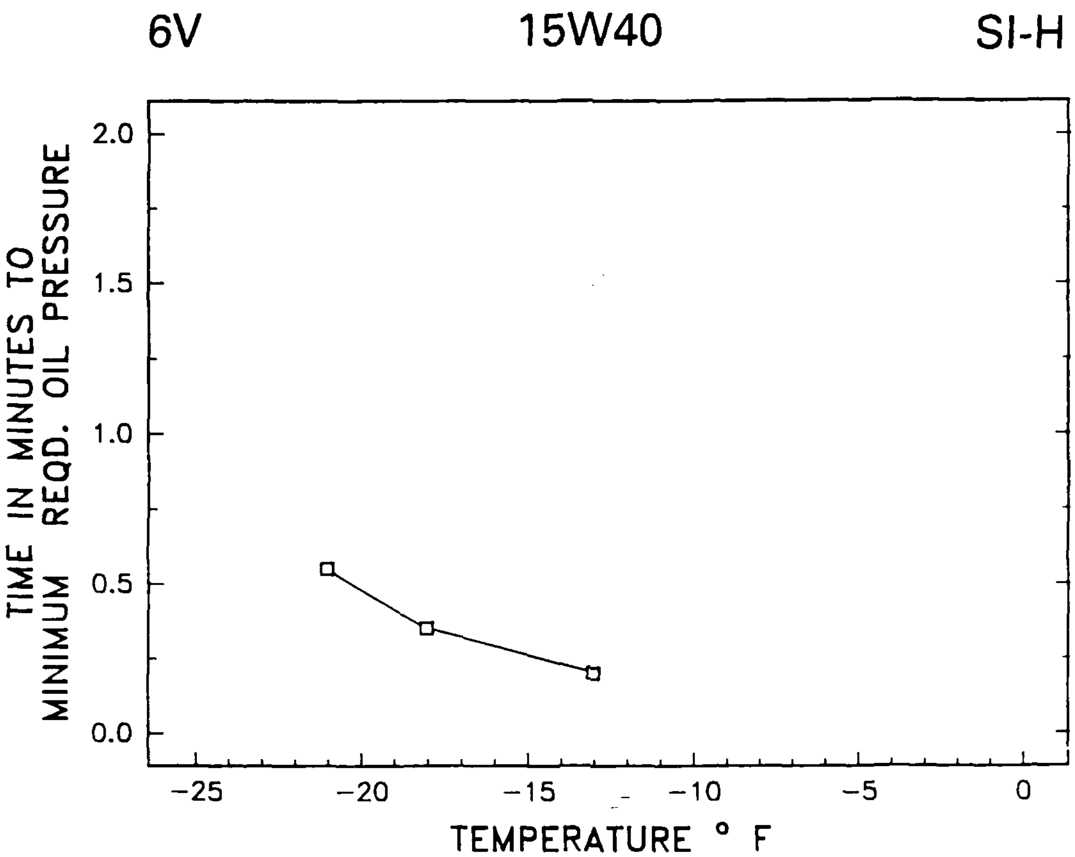


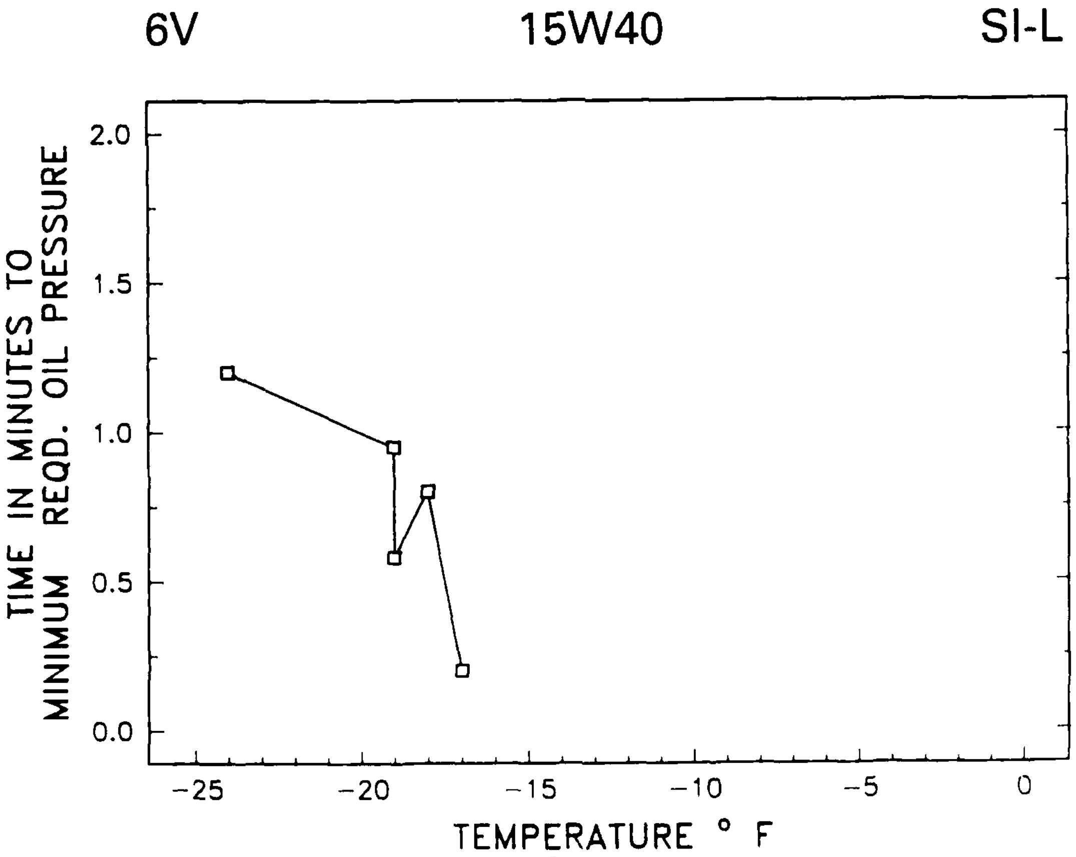
6V 15W40 OIL NO. 2



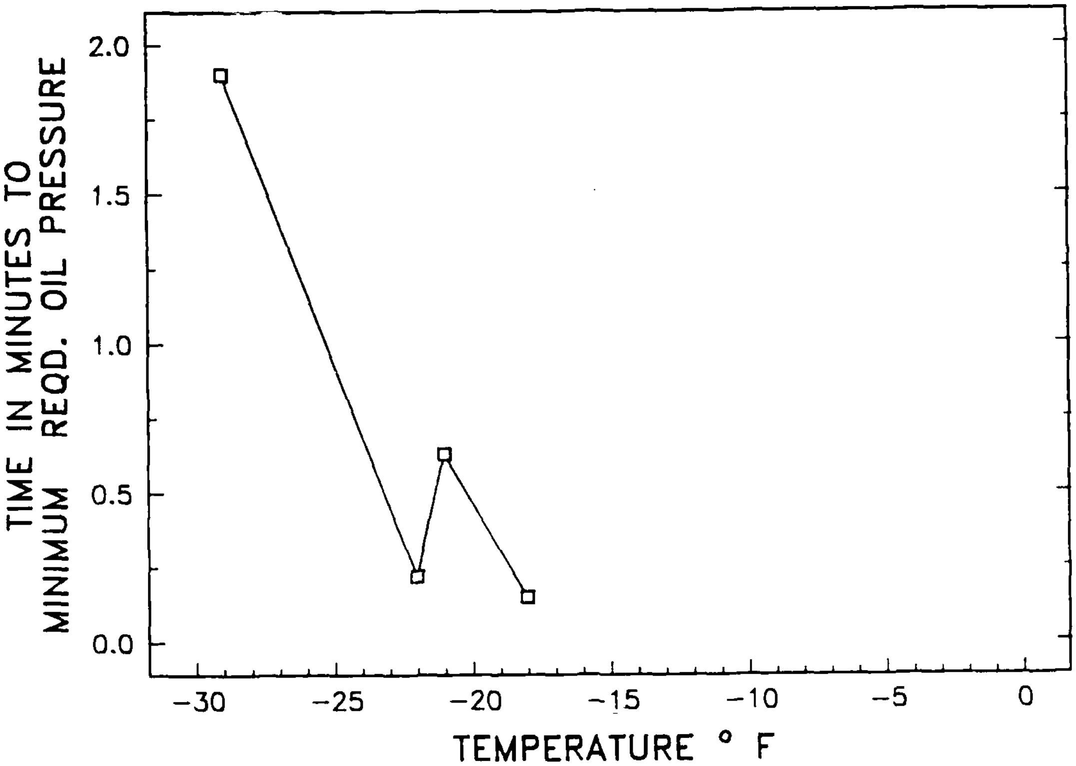

6V
15W40
OCP-L
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
TEMPERATURE ° F


6V
15W40
OCP-H
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
TEMPERATURE ° F

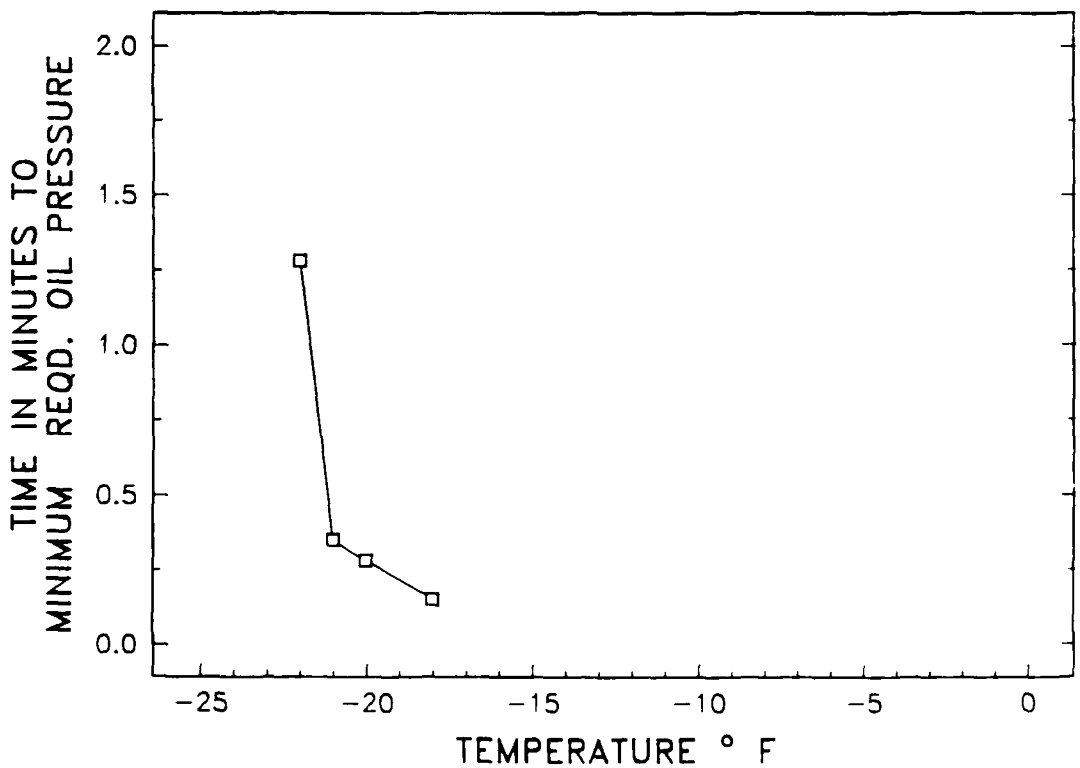

6V
15W40
SI-H
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−25
−20
−15
−10
−5
0
TEMPERATURE ° F

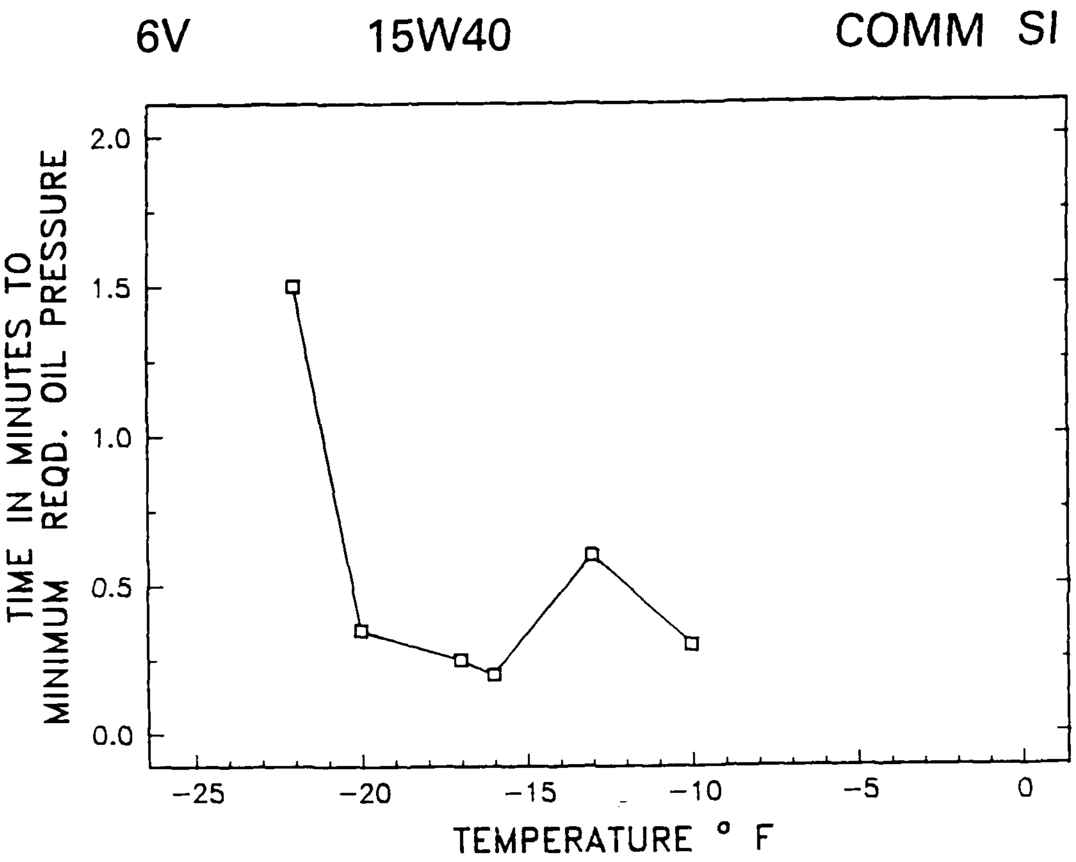

6V
15W40
SI-L
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−25
−20
−15
−10
−5
0
TEMPERATURE ° F

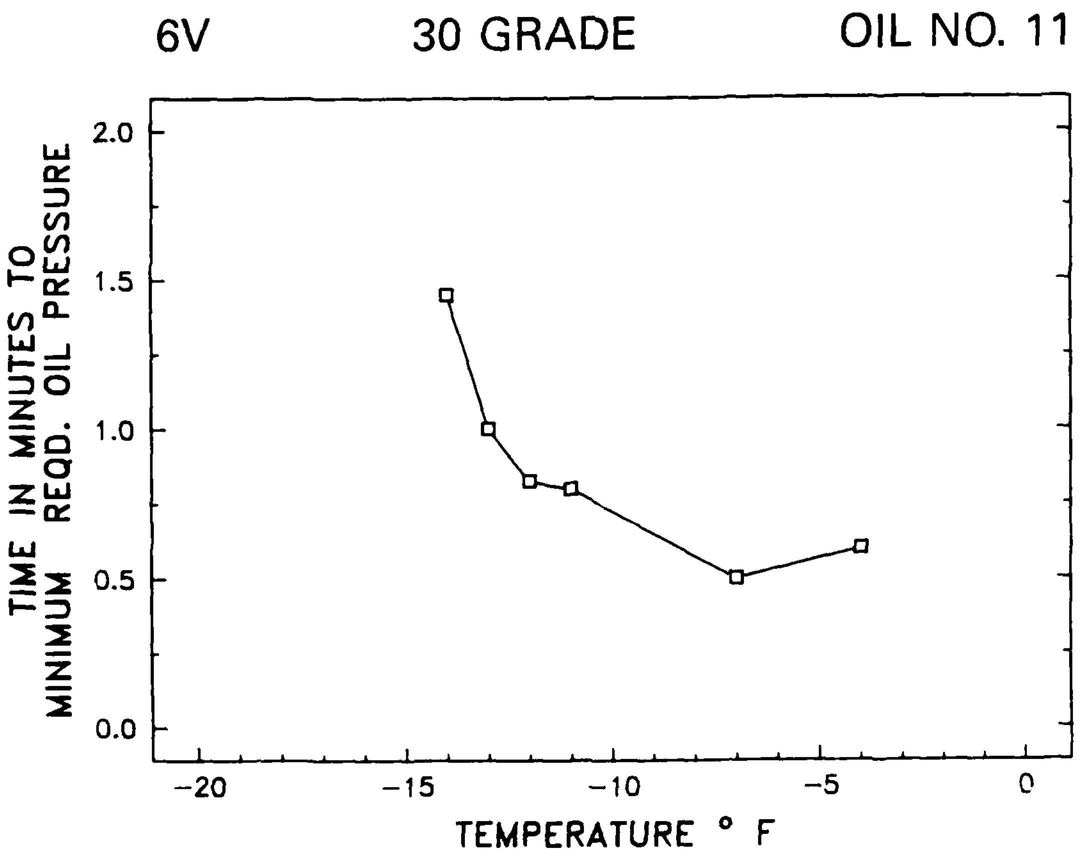
6V 15W40 PMA-L



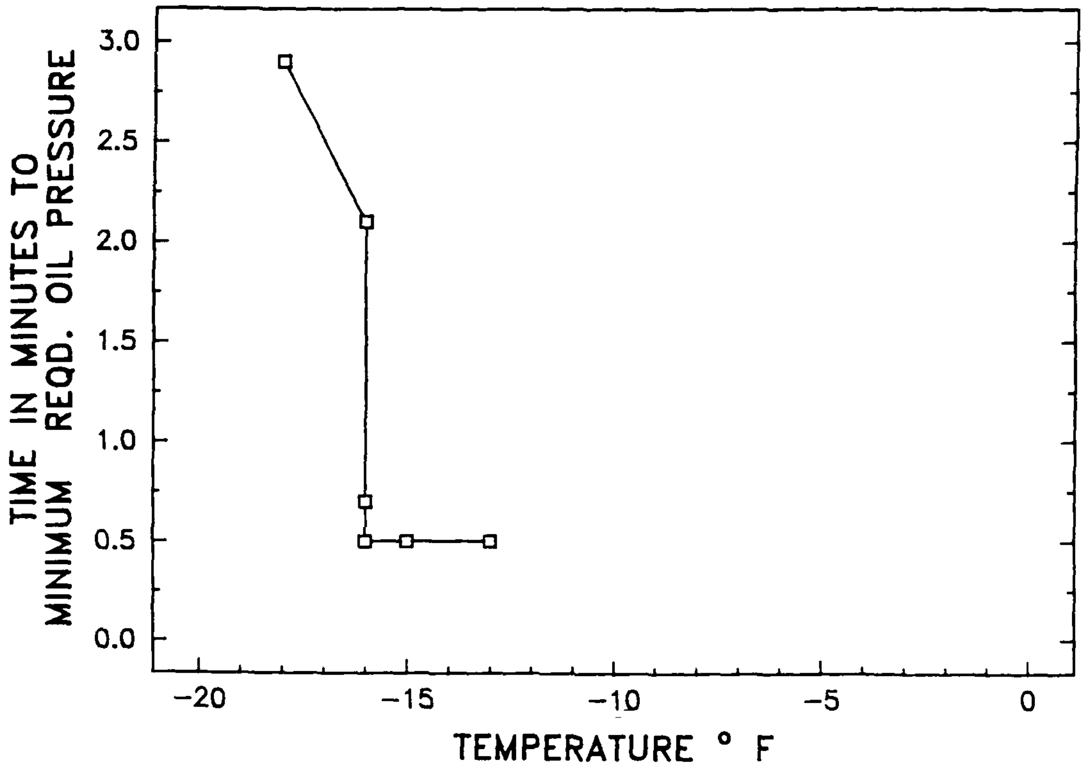
6V 15W40 PMA-H



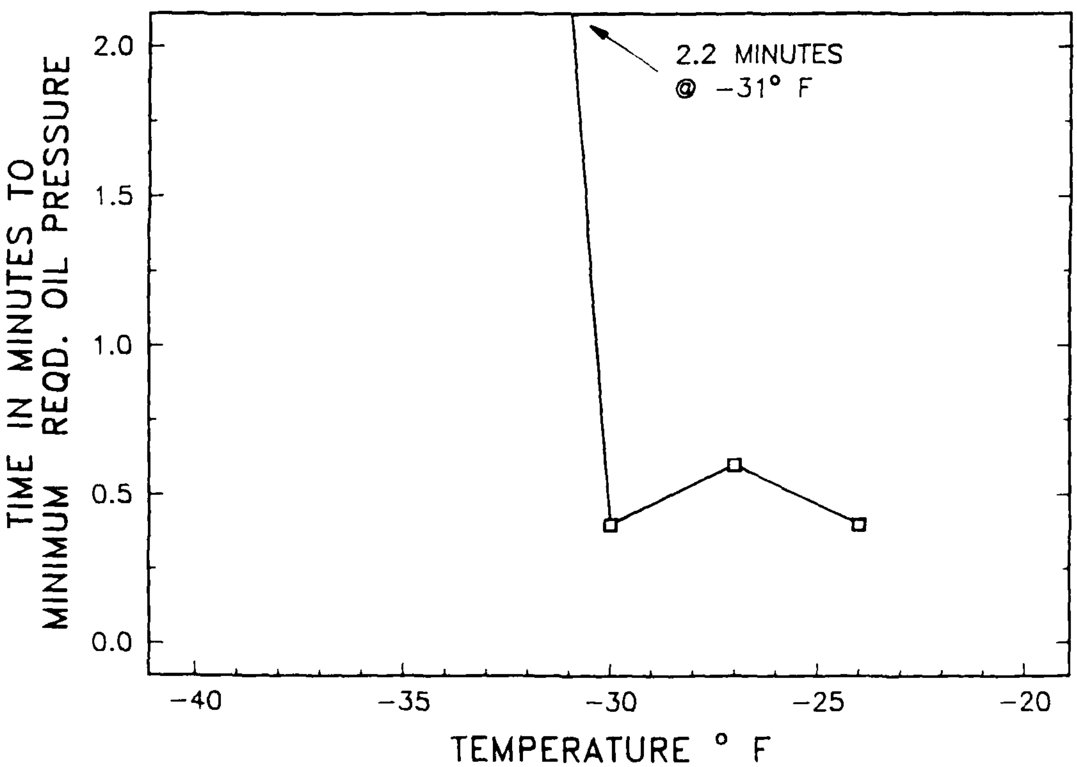

6V
15W40
COMM SI
TIME IN MINUTES TO MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
TEMPERATURE ° F


6V
30 GRADE
OIL NO. 11
TIME IN MINUTES TO MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
-20
-15
-10
-5
0
TEMPERATURE ° F

6V 30 GRADE OIL NO. 12



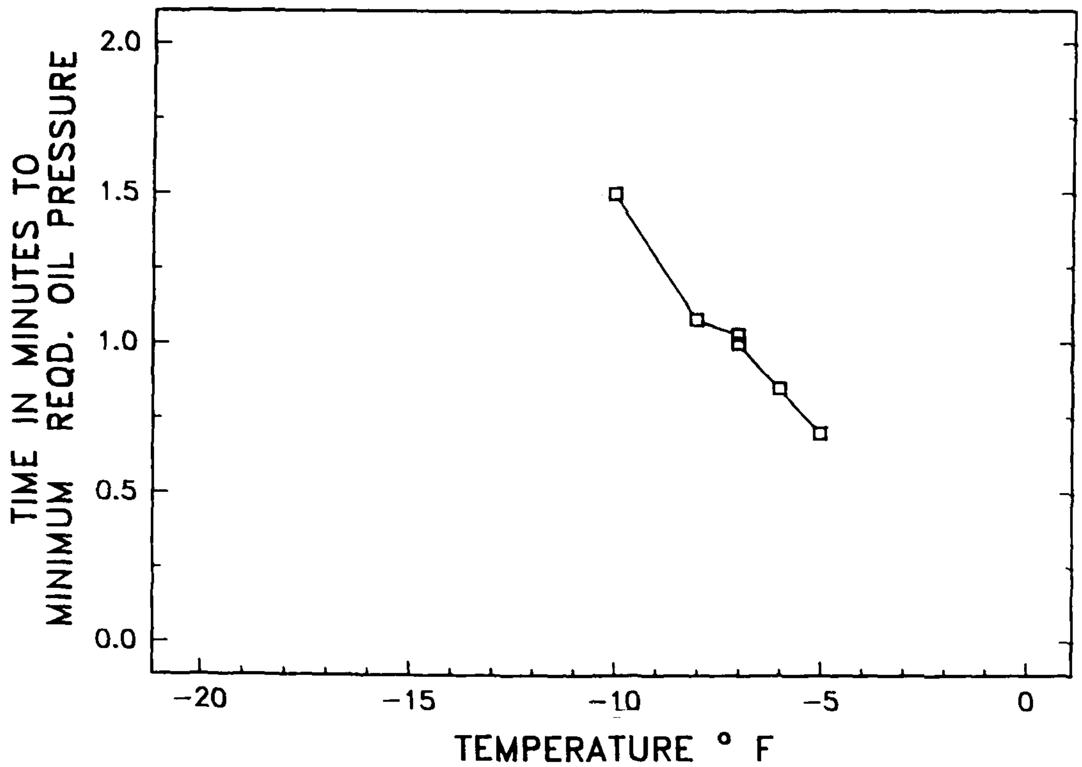
6V 10W OIL NO. 13



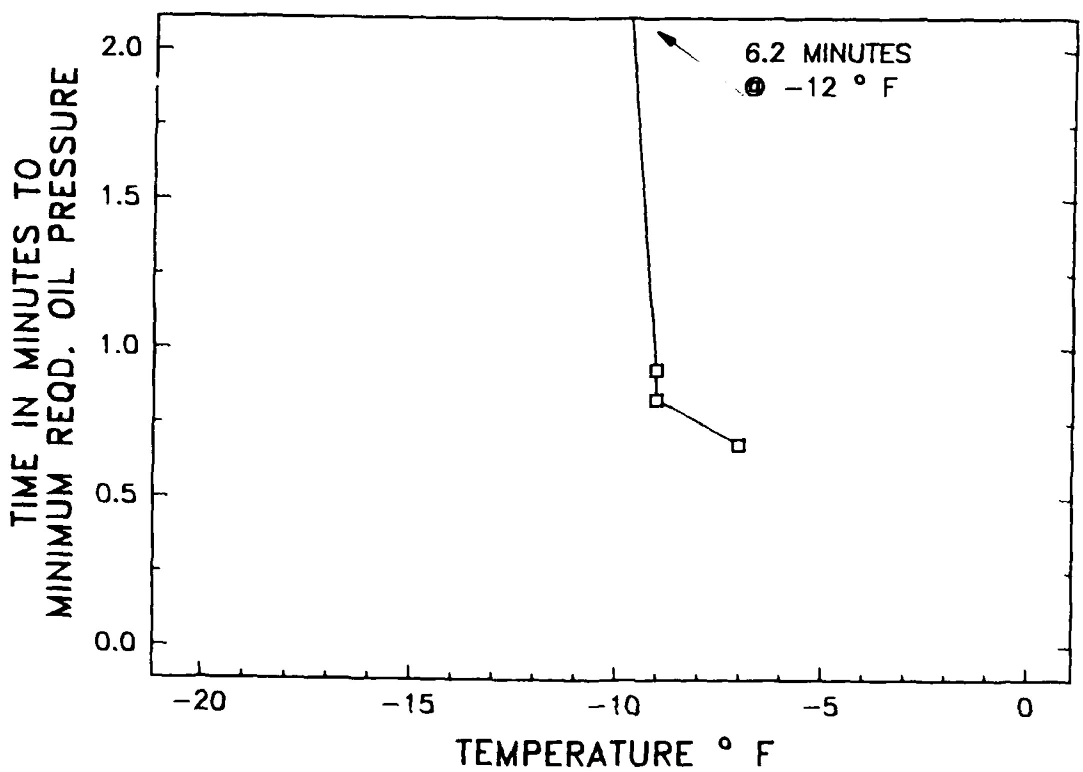
APPENDIX F

Low-Temperature Oil Pumpability in the Cummins VTA-903-T Engine

CU903 15W40 OIL NO. 1



CU903 15W40 OIL NO. 2



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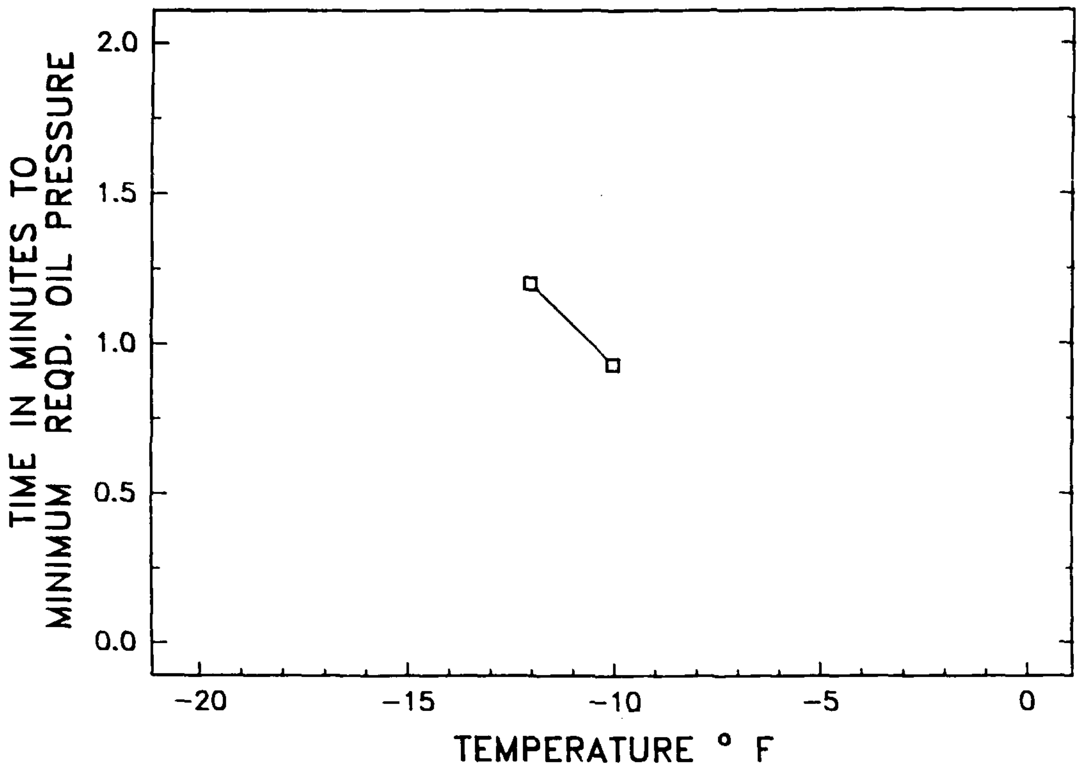

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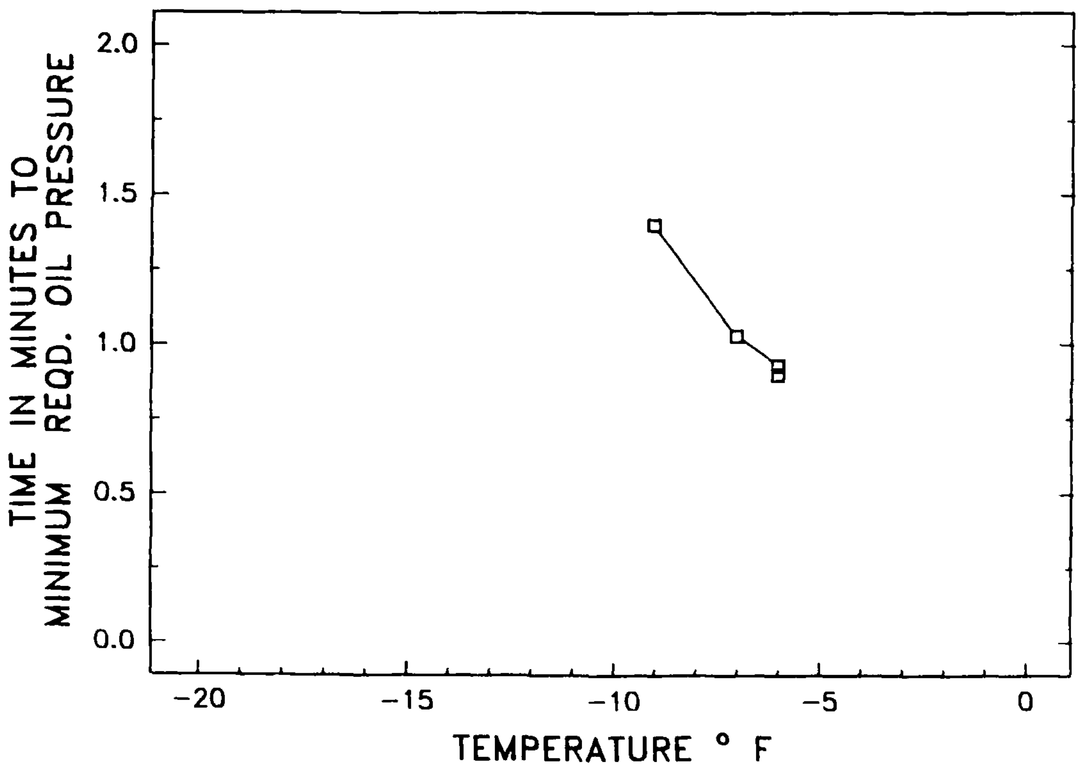
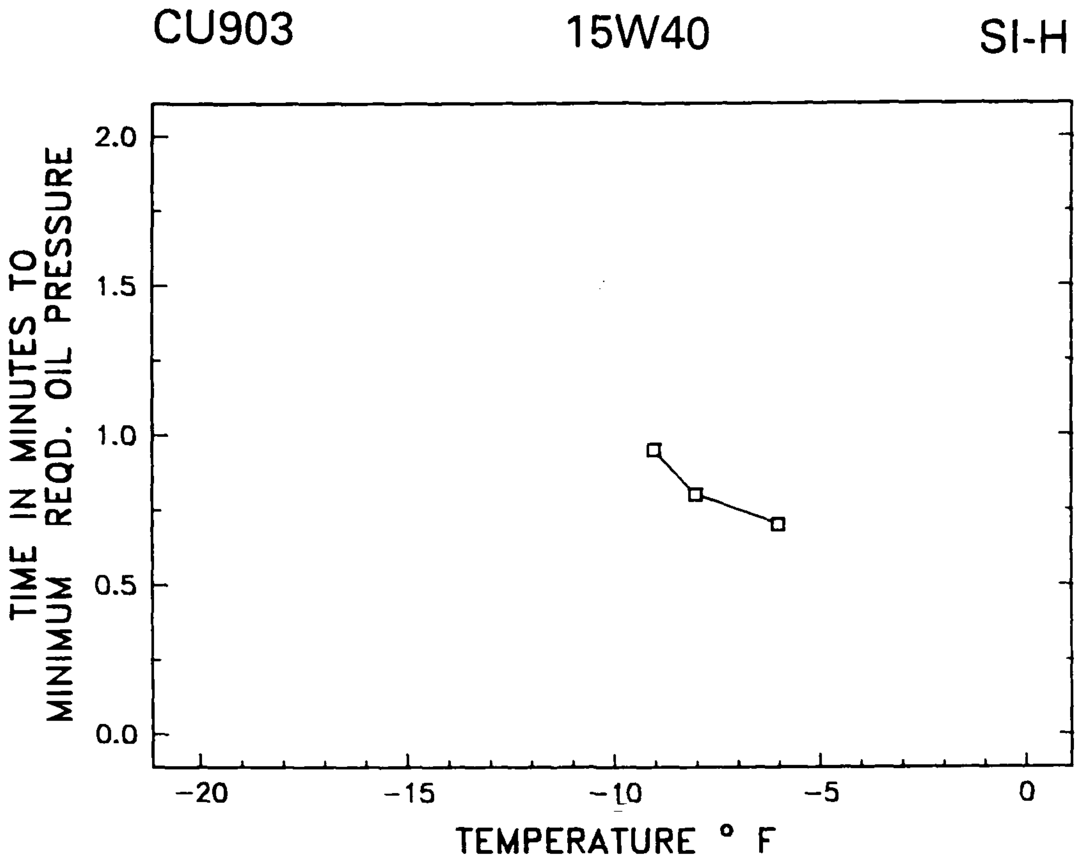
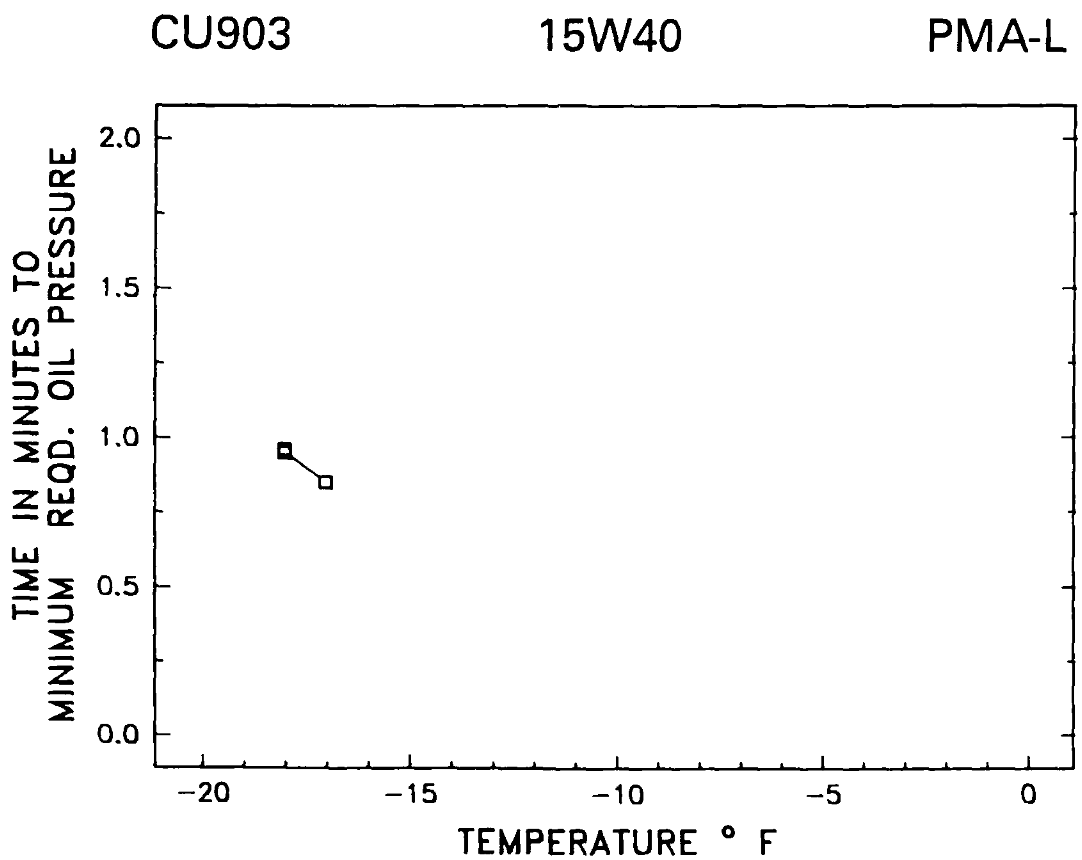


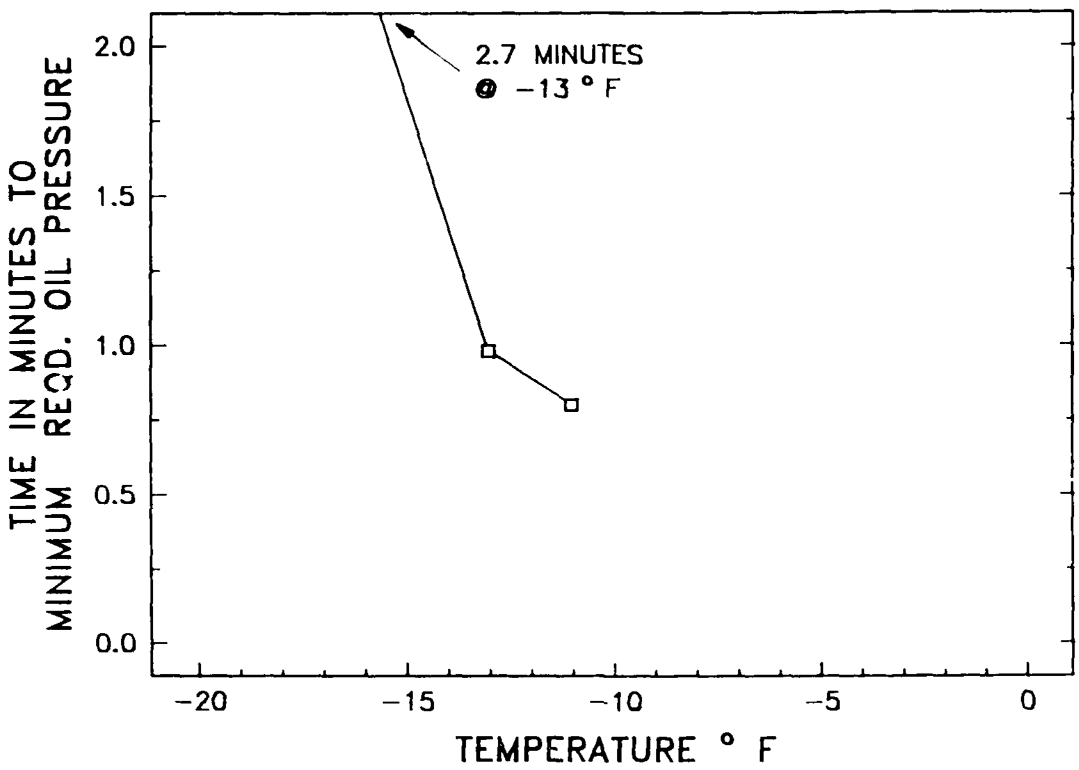


CU903
15W40
SI-H
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F

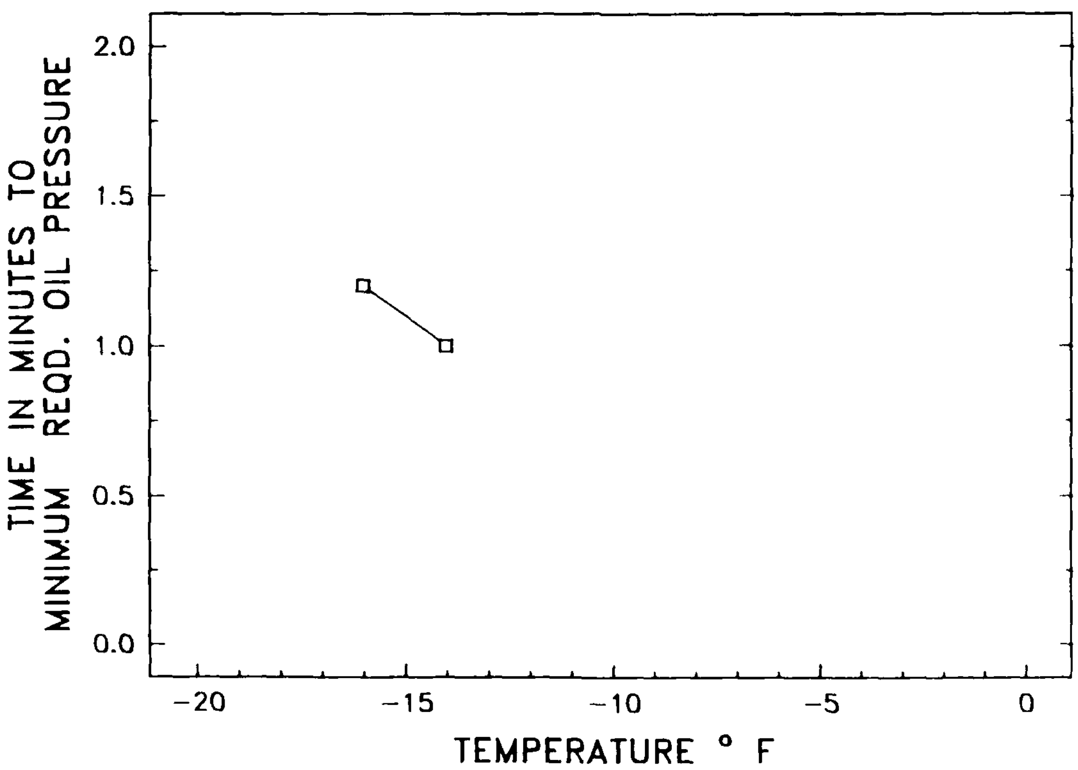


CU903
15W40
PMA-L
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F

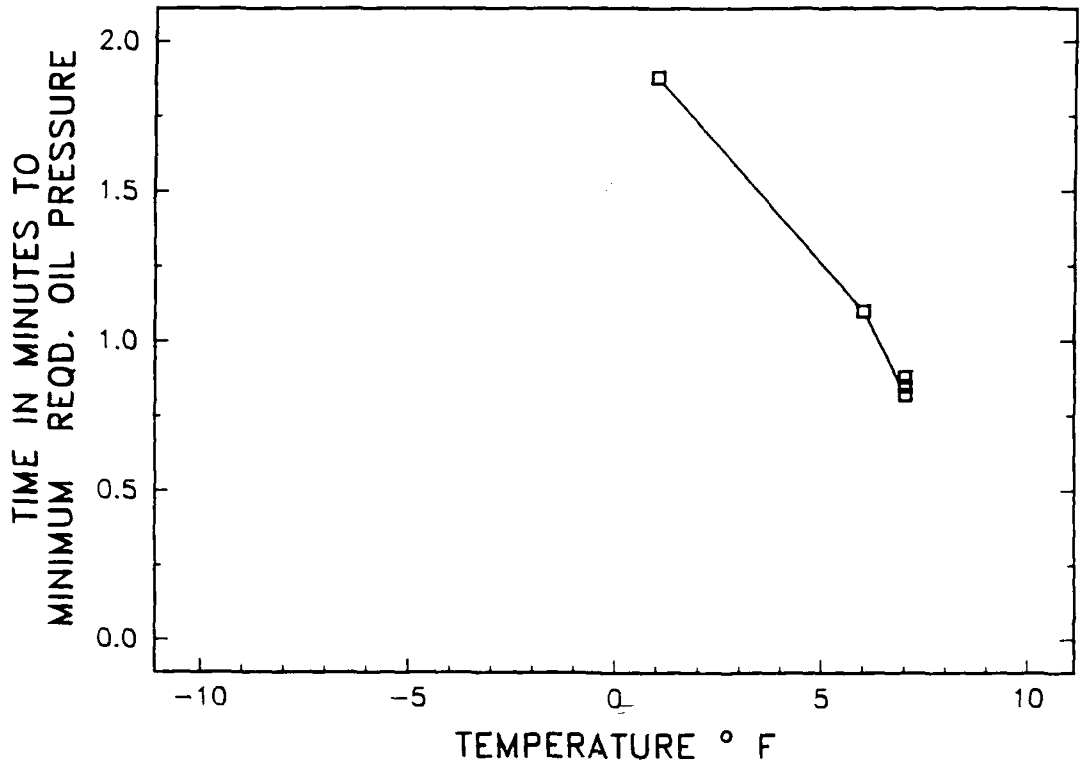
CU903 15W40 PMA-H



COMM PMA 15W40



CU903 30 GRADE OIL NO. 11 75 VI



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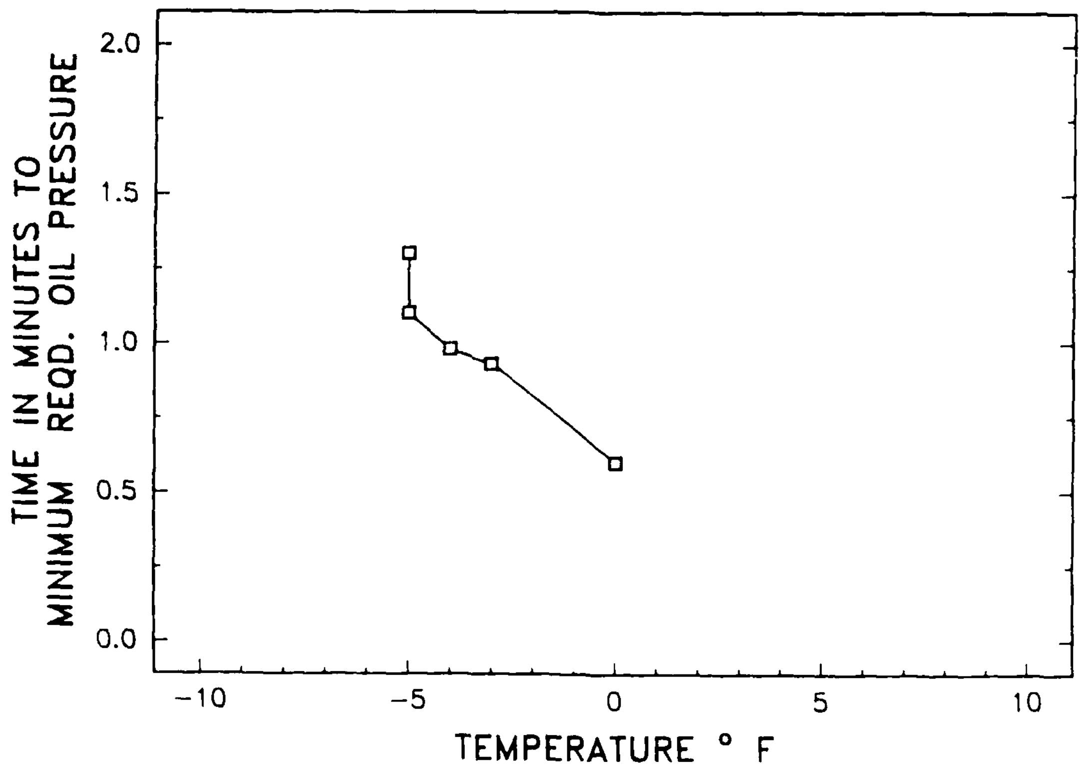
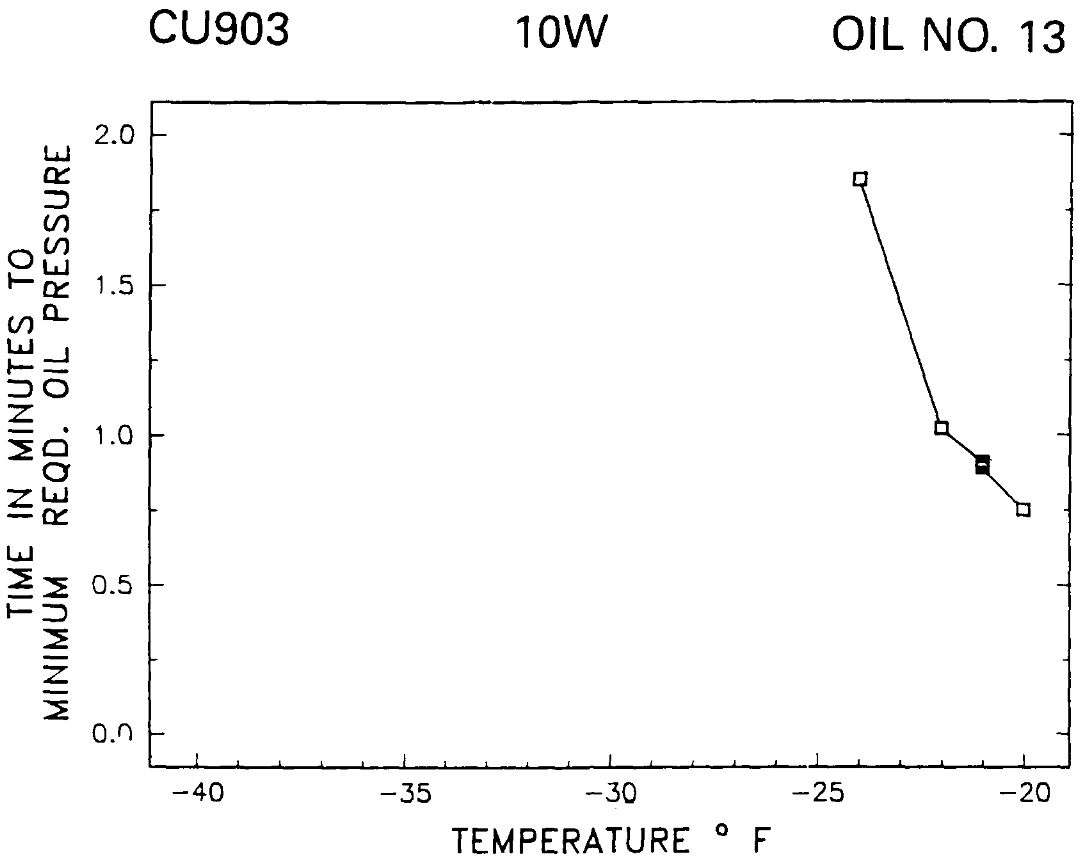
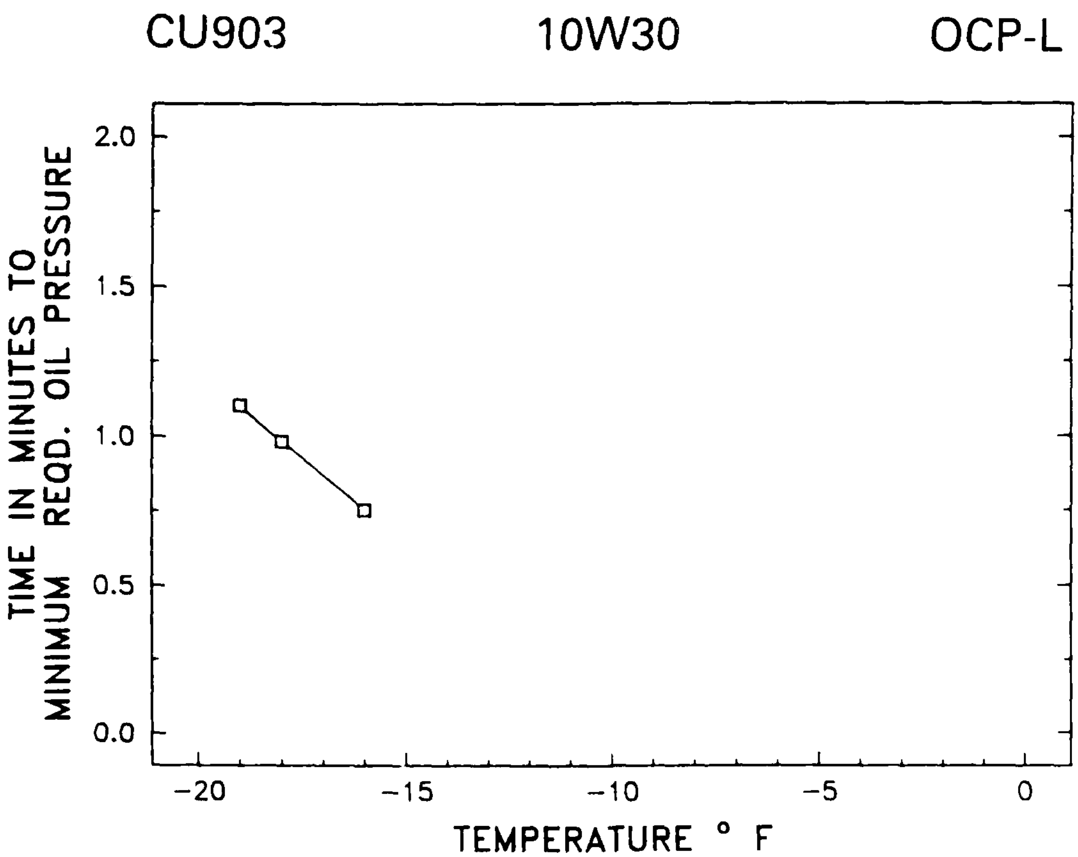


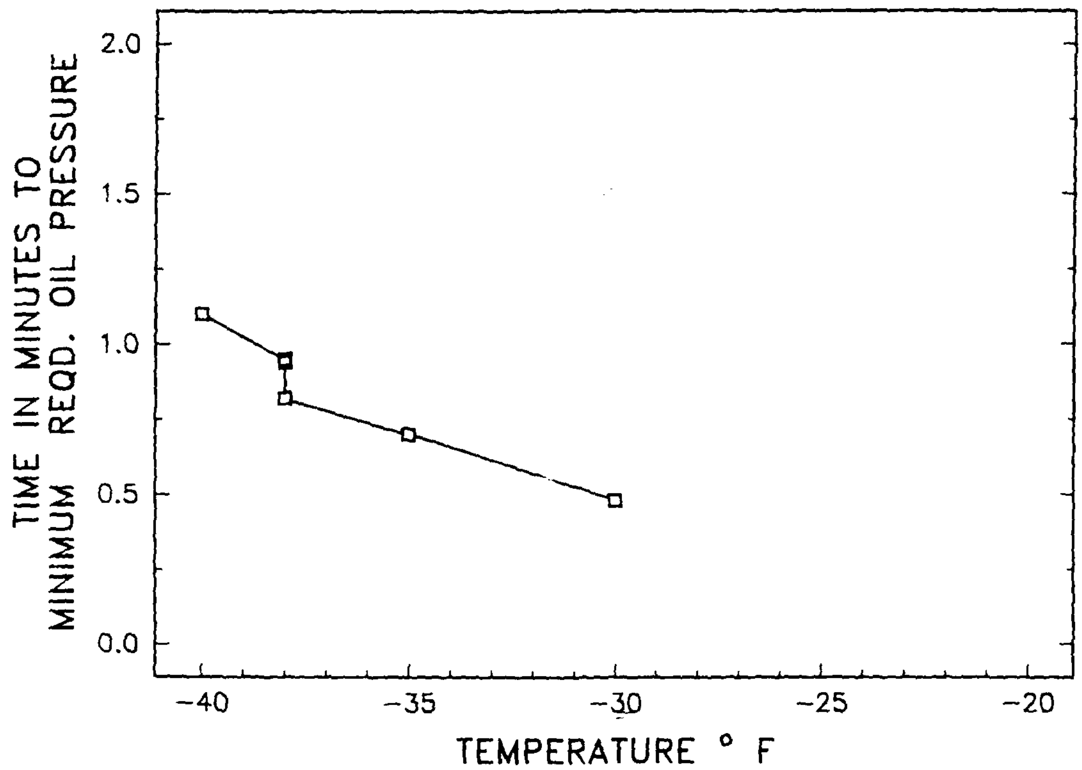


CU903
10W
OIL NO. 13
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−40
−35
−30
−25
−20
TEMPERATURE ° F



CU903
10W30
OCP-L
TIME IN MINUTES TO
MINIMUM REQD. OIL PRESSURE
2.0
1.5
1.0
0.5
0.0
−20
−15
−10
−5
0
TEMPERATURE ° F

CU903 5W30 OIL NO. 16



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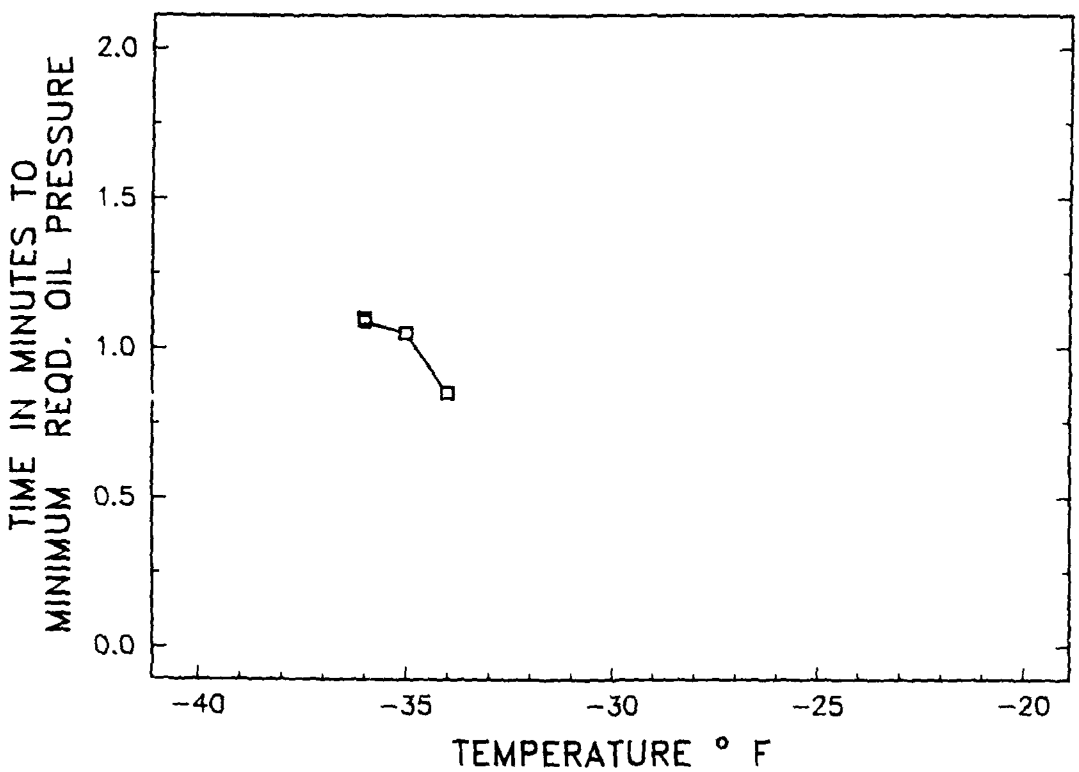

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